Nuclear Energy

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Preface

In order to understand the production, use, and dangers of nuclear energy it is necessary to know something about atoms and their structure. Rather than simply state that an atom is a nucleus surrounded by electrons, and that the nucleus contains protons and neutrons, I have tried to give the reasons why physicists have come to picture the atom in this way. The present picture of the atom in terms of quantum mechanics is, of course, far more sophisticated. I have not given this quantum-mechanical picture because it is not essential for our purpose and it would confuse rather than enlighten someone making his first acquaintance with the subject. Similarly, in electrolysis I felt it would be confusing to deal with 'relative ionic concentrations' and the electrochemical series. Instead, I have taken a very simple picture of electrolysis, in the main following Faraday's accounts in his *Experimental Researches in Electricity* (Everyman Library, Dent). In the few places where mathematics is introduced only the simple processes of addition, subtraction, multiplication, and elementary algebra are required.

At all times I have tried to keep in mind a reader who is interested in science and its implications but who has had little or no formal training in physics. Wherever possible, therefore, new words are explained as they are introduced.

Although the book has been produced primarily for young people, I hope that anyone who is interested in science or who has a concern for the possible mis-use of nuclear energy will find it useful.

With regard to the actual production of the book, I am particularly grateful to the staff of the Clarendon Press and their associates for their help at every stage and for presenting the final result in such an expert and attractive manner.

L. A. R.

Lytham St. Annes,
May, 1963.

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The British Broadcasting Corporation
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Figures 34 and 36 are from a talk given by P. T. Fletcher to the Institute of Marine Engineers on 28 March 1957. They have been slightly modified.

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Pye Instrument Group and Pye Atomics Division

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Molins Machine Company Limited

Chapter 1

What nuclear energy can do

THIS book consists of millions of atoms. So does the chair you sit on, the air you breathe, your own body—everything, in fact, which we can detect in this world with our senses. Each atom is a vast store of energy. But so far scientists have only learned how to release the energy from certain types of atom.

Everyone has heard of the atomic bomb and its terrifying power for destruction. In any explosion, such as that of an ordinary bomb, energy is released very quickly, and it is that which causes the destruction. In an atomic bomb the amount of energy released is vastly greater, and since the release is made in an incredibly short time—a fraction of a millionth of a second—the destruction is also vastly greater. The bomb is in fact a colossal waste of energy.

Scientists have now succeeded in controlling this release of energy and using it for peaceful ends. In Britain, a steadily increasing amount of electricity is being produced by nuclear power stations. As the demand for power increases year by year this is very timely, for the country's resources of coal are not inexhaustible, and we have little water power.

Apart from its use as fuel in power stations, nuclear energy is now also being used as a fuel to drive ships. Several submarines and surface vessels, including the Soviet icebreaker *Lenin* and the United States passenger cargo ship *Savannah*, have nuclear power plants.

The knowledge of the atom that man has gained in releasing nuclear energy is also opening up many other possibilities. In medicine, for example, radioactive chemicals are used in the diagnosis and treatment of diseases. In agriculture, radioactive atoms tell scientists exactly how plants absorb their food, and so help the farmer to choose the appropriate fertilizer and to feed it to the plant in the best possible way. Again in industry, radioactive materials are used in many ways: for example, to record the level of molten steel inside a furnace where it is too hot to use an ordinary gauge, or to measure the thickness of steel or paper sheets. The pure research chemist uses radioactive materials in his study of chemical reactions. Even the archaeologist has gained from our knowledge of the atom: he can now tell the age of some ancient object he has found by the amount of radiation it has given off during the centuries it has been buried.

There is no doubt that before long scientists will discover a great many more ways of harnessing the atom to man's use. But before we can understand exactly how these fascinating new developments have taken place we must find out more about what atoms are like and how they behave.

Chapter 2

The discovery of the atom

EVER since man began to explore the physical world in which he lives, he has tried to divide the substances around him in order to find out what they are made of. By countless experiments chemists have learned that there are some substances, silver for example, which cannot be divided up into anything more simple. Such substances are called elements. It is now known that ninety-two elements exist naturally. They include hydrogen, gold, silver, sodium, chlorine, and uranium. We shall see later how new elements can actually be made in the laboratory (p. 48).

Sometimes two or more elements combine to form what is called a compound. Thus when the elements sodium and chlorine combine they form the compound sodium chloride (common salt). The elements hydrogen and oxygen combine to form the compound we know as water (Fig. 1).

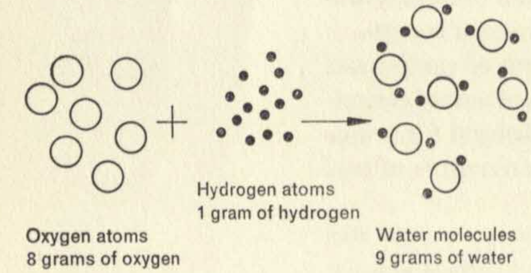

Fig. 1
Each oxygen atom combines with two atoms of hydrogen to form a molecule of water.

Each compound is always made up of its elements combining in the same proportion: for a given compound the same elements cannot combine in any different proportion. Thus, 1 gram of hydrogen always combines with 8 grams of oxygen to produce 9 grams of water. If we try to combine 2 grams of hydrogen with 8 grams of oxygen we get 9 grams of water plus 1 gram of hydrogen left over: if we try to combine $\frac{1}{2}$ gram of hydrogen and 8 grams of oxygen we get $4\frac{1}{2}$ grams of water plus 4 grams of oxygen left over.

It was to explain observations such as these that John Dalton, a schoolmaster in Manchester, put forward his Atomic Theory in 1808. He reasoned in the following way: water can exist in three forms—as a solid, ice; as a liquid, water; and as a gas, steam. These different forms could be explained if all substances, whether liquids, solids or gases, were made of a vast number of extremely small particles. These particles must be held together by a force of attraction. In a solid this force is very strong, and this accounts for the strength and rigidity of solids. In a liquid the force is not quite so strong, allowing the liquid to flow and take the same shape as the container. In a gas the force is too weak for the particles to have any appreciable effect on each other, and so a gas spreads itself evenly throughout the space it occupies.

In suggesting that matter was composed of particles in this way, Dalton was not putting forward a new idea. For over 2 000 years the word 'atom' had been used in theories about the structure of matter, to describe the smallest particle of a substance that can exist. In fact, the word 'atom' means 'that which cannot be divided', and earlier scientists used the word for the smallest conceivable particle of any substance, whether element or compound. *Since Dalton's time the word has been used to describe the smallest particle which shows the characteristics of an element. All the atoms of any particular element are like each other but different from those of other elements.* Strictly speaking, the word 'atom' is now used incorrectly, since atoms can be divided. But if an element has its atoms divided it becomes a different element, for instance uranium in certain circumstances turns to lead.

The relative weights of atoms

The new idea of Dalton's theory was that it is possible to compare the relative weights of atoms. This followed from experiments such as the one to produce water mentioned above. Dalton said that if 1 atom of hydrogen combined with 1 atom of oxygen to form 1 molecule of water, the weight of the oxygen atom must be eight times that of the hydrogen atom, since 8 grams of oxygen combine with 1 gram of hydrogen. *The word 'molecule' (little bundle) was actually first used in 1811 not by Dalton but by an Italian contemporary, Avogadro, to mean the particle that is formed when two or more atoms combine to form either an element or a compound.*

Dalton's assumption that there was 1 atom of hydrogen in a molecule of water was wrong. Each molecule of water actually contains 2 atoms of hydrogen. This made Dalton's arithmetic incorrect, and the weight of an oxygen atom is really sixteen times that of an hydrogen atom. But his idea was sound, and strikingly original.

The number of atoms in a molecule

The number of atoms in a molecule of, say, hydrogen, can be found by the following experiment. When equal volumes of v c.c of hydrogen and chlorine are combined together they produce a volume $2v$ c.c of hydrogen chloride:

$$\underset{v\ \text{c.c}}{\text{Hydrogen}} + \underset{v\ \text{c.c}}{\text{Chlorine}} \longrightarrow \underset{2v\ \text{c.c}}{\text{Hydrogen chloride}}$$

Avogadro had suggested that under the same conditions of temperature and pressure equal volumes of all gases contain the same number of molecules. This suggestion, or hypothesis as the scientist calls it, has been used in countless calculations, each of which has been checked by experiment and found to be correct. This shows that Avogadro's hypothesis is a valid one.

Let us suppose then, that there are n molecules in v c.c of hydrogen.

Therefore, using Avogadro's hypothesis: under the same conditions of temperature and pressure there will be *n* molecules of chlorine in *v* c.c of chlorine, and there will be 2*n* molecules of hydrogen chloride in 2*v* c.c of hydrogen chloride.

Re-writing the equation above we get:

$$\underset{n\text{ molecules}}{\text{Hydrogen}} + \underset{n\text{ molecules}}{\text{Chlorine}} \longrightarrow \underset{2n\text{ molecules}}{\text{Hydrogen Chloride}}$$

And dividing this throughout by *n* gives:

$$\underset{1\text{ molecule}}{\text{Hydrogen}} + \underset{1\text{ molecule}}{\text{Chlorine}} \longrightarrow \underset{2\text{ molecules}}{\text{Hydrogen chloride}}$$

Each molecule of hydrogen chloride must contain at least 1 atom of hydrogen and 1 atom of chlorine—since an atom is the smallest part of an element. Thus in the 2 molecules of hydrogen chloride there must be at least 2 atoms of hydrogen and 2 atoms of chlorine. These 2 atoms can only come from the single molecules we started with, so each molecule of hydrogen must contain at least 2 atoms. Similarly each molecule of chlorine must contain at least 2 atoms of chlorine.

It is equally true of course that the hydrogen or chlorine molecules could contain 4, 6, 8, or any other even number of atoms. When we have this sort of situation the scientist always takes the simplest figures as being the best. Since all the reactions in which hydrogen and chlorine play a part can be understood by assuming their molecules to be made up of only 2 atoms, we consider hydrogen and chlorine gases to consist of 2-atom molecules.

Similar reasoning, backed always by experiment, shows that a molecule of oxygen also contains 2 atoms, and that a molecule of water consists of 2 atoms of hydrogen and 1 atom of oxygen.

Standards of atomic weight

The weights of atoms were first expressed as so many times the weight of the hydrogen atom. Thus, the atomic weight of hydrogen was called 1 and oxygen therefore had an atomic weight of just over 16.

This was an unfortunate choice, since comparatively few elements form compounds with hydrogen, and those which do are difficult to analyse. To overcome this difficulty, chemists chose oxygen as the standard to which all other atomic weights were compared. This was because all the early measurements of atomic weights relied on combining the element in question with oxygen (combustion), or displacing the oxygen from a compound of the element which contained it (reduction). Since they were choosing a new scale any value could be taken for the atomic weight of oxygen and then the weights of other elements compared with this. Several such scales were suggested; one took the atomic weight of oxygen to be 1, another took it to be 10, and yet another said 100 would be best. But in order to change things as little as possible, the scale O = 16 was finally adopted in 1885. On this scale the atomic weight of hydrogen was 1·008 instead of being exactly 1 as it was before; any other of the proposed new scales would have produced a much greater change in the atomic weight of hydrogen, and the atomic weights of all the other elements as well.

Some fifty years later than this, in 1935, it was realized that even the O = 16 scale was not satisfactory. It had been discovered that oxygen contains not only atoms of weight 16 units but also atoms weighing 17 and 18 units as well. These were called isotopes † of oxygen and labelled O^{16}, O^{17}, and O^{18} respectively. And unless we know just how many of each of these different atoms the oxygen we are using contains it will clearly lead to incorrect results if we assume they all have a weight of 16 units.

Now, more accurate values for atomic weights can be obtained experimentally by comparing the weights of different atoms with the weight of the atoms of the isotope of carbon, C^{12}.

In 1960 a new scale of atomic weights with $C^{12} = 12$ exactly as the standard was agreed on, to enable full use to be made of precise modern experimental techniques.

Actual weights and sizes of atoms

We have seen how the relative weights of atoms can be compared, but is it possible to get some idea of how much they actually weigh, or how big they are? Their sizes and weights are, in fact, so unimaginably small that there is no question of their being measured directly.

The first reliable estimate of these values was made by the German scientist Loschmidt in 1865. It had already been shown that the viscosity, or resistance to flow, of a gas could be related to the size of the molecules and the number of molecules present in 1 cubic centimetre. This was expressed in the form of a mathematical equation. Loschmidt pointed out that these two quantities could also be related to the density of the liquid formed when the gas condensed. Thus by measuring the viscosity of the gas and the density of the liquid two equations were obtained and by solving them the values for the size and number of molecules in 1 cubic centimetre could be calculated. These were absolute values but since several assumptions had been made in getting the equations they were only approximate ones. Using this method he calculated that oxygen molecules were one ten-millionth of a centimetre in diameter and that 1 c.c of oxygen gas contained about 200 000 000 molecules.

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† For a fuller explanation of the word 'isotope' see p. 33.

The weight of 1 c.c of oxygen gas is 0·001429 of a gram, and by dividing this by 200 000 000 he found the weight of 1 molecule of oxygen to be 0·000000000007145 of a gram. Since a molecule of oxygen contains 2 atoms, the weight of 1 atom is one-half this quantity.

As a further example of how small these quantities really are, 7 million atoms of hydrogen placed side by side would stretch just 1 millimetre. It would take over a million, million, million atoms of hydrogen to weigh only a millionth of a gram.

Clearly it is impossible to see individual atoms, even with the aid of the most powerful of modern electron microscopes with a magnification of 120 000. However, very large molecules have been photographed and have been found to be of different sizes.

A rough value for the diameter of large oil molecules can be obtained in the following way. A measured volume of the oil is spread out on the surface of some water. The oil film is then stretched out until it begins to break up into patches. It must now be at its thinnest—let us assume that it is only 1 molecule thick. The total area of the patches is measured and the thickness of the film found by dividing the volume by the area. This gives the diameter of the oil molecules.

We must remember that Dalton and his fellow scientists thought of atoms and molecules as if they were solid and indivisible. Admittedly, different elements had atoms of different sizes, and different compounds had molecules of different sizes, but they were still looked upon as solid and indivisible. Although Dalton and others had made great progress in comparing the weights of atoms and molecules, and in getting approximate values for their actual weights and sizes, they, like all truly great scientists, realized how little they still knew.

Chapter 3

The discovery of the electron

THE first indication that atoms were not like solid marbles came with the discovery of the electron. This was not a discovery that took place suddenly, like the finding of a lost cricket ball; it was rather the accumulation of evidence over a period of some seventy years until the existence of the electron could no longer be doubted. Naturally, during such a long period of time many theoretical calculations and experiments were carried out. As it is impossible to include them all here we will just look at the more important ones.

Electrolysis

The story started during the years 1831–34 when Michael Faraday investigated what happened when he passed a current of electricity through different liquids, in particular through water in which some chemical was dissolved. When he passed the current through a solution of sodium chloride (common salt) in water the gas chlorine was given off at the positive plate, and hydrogen was given off at the negative plate.

Any process such as this is called electrolysis. Electrolysis occurs whenever a liquid is split up chemically by passing an electric current through it. Most liquids which conduct electricity exhibit electrolysis, the notable exceptions being molten metals such as mercury.

During electrolysis substances are liberated from the solution at one or both of the plates which take the current into and out of it. Take the case of hydrochloric acid (HCl). When a current is passed through the acid, chlorine is given off at the positive plate, and hydrogen at the negative plate. The chlorine part of the hydrochloric acid travels to the positive plate where it is given off as a gas, and similarly the hydrogen part travels to the negative plate. *The parts of substances which travel through solutions during electrolysis were called ions by Faraday*. The term ion comes from the Greek word meaning traveller.

Another example is the electrolysis of copper sulphate solution. In this case copper is deposited on the negative plate when the current is passed. This is the basis of the process known as electro-plating in industry in which objects are coated with different metals by electrolysis. Teaspoons are silver-plated and bicycle parts are nickel- or chromium-plated in this way.

In one of Faraday's many experiments he passed a current through sodium chloride solution. He collected the hydrogen given off at the negative plate

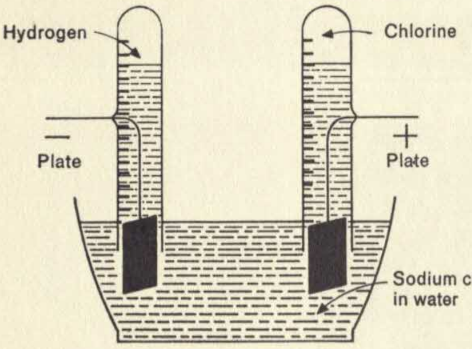

Fig. 2

Faraday's electrolysis experiments.

and also the chlorine given off at the positive plate when a definite quantity of electricity was passed through the solution (Fig. 2). In fact he found that whenever he passed the same quantity of electricity through any solution he always got the same amount of substance liberated. If twice the quantity of electricity was passed, twice the amount of the substance was liberated; if only half the quantity of electricity was passed only half the quantity of the substance was liberated, and so on. From the many experiments he did Faraday found that the weights of substances liberated were always directly proportional to the quantity of electricity passed through the solution.

He also knew that in chemical reactions elements always combine in the same proportion by weight—as we saw in Chapter 2. To express this quantitatively chemists have defined a quantity known as the equivalent weight of an element. The equivalent weight of an element is the weight of the element which will combine with 1 gram of hydrogen or 8 grams of oxygen. When any two elements combine they always do so in the ratio of their equivalent weights. An example will make the use of equivalent weights clear:

8 grams of oxygen combine with 1 gram of hydrogen.
12 grams of magnesium combine with 8 grams of oxygen.

Therefore the equivalent weight of oxygen is 8 and the equivalent weight of magnesium is 12. When magnesium and oxygen combine to form magnesium oxide they always combine in the ratio of 12 parts by weight (e.g. grams or pounds) of magnesium to 8 parts by weight of oxygen. Faraday determined the quantity of electricity needed to liberate the equivalent weights of different elements in electrolysis and found it to be exactly the same in each case. Thus the same quantity of electricity that liberates 8 grams of oxygen during electrolysis would, if passed through a solution containing magnesium, liberate 12 grams of magnesium. This same quantity of electricity will liberate the equivalent weight of any element present in a solution when it is electrolyzed—this is, always provided the solution can be electrolyzed, of course.

Faraday had shown that to deposit a certain amount of a substance in electrolysis required a definite quantity of electricity, and that to deposit the equivalent weight of any element the same quantity of electricity was always required.

Now if the same quantity of electricity is always needed to deposit the equivalent weight of an element, simply dividing this amount by the equivalent weight will tell us the quantity of electricity needed to deposit 1 gram of the element. By dividing this by the number of atoms in 1 gram the quantity of electricity needed to deposit 1 atom is found.

If we do this for the hydrogen and chlorine produced in the electrolysis of hydrochloric acid the result is that hydrogen atoms and chlorine atoms require the same quantity of electricity to deposit them. From these results scientists built up a picture of what happens in electrolysis. This picture, or theory, is shown in Fig. 3, in which the chemical substance electrolyzed is hydrochloric acid.

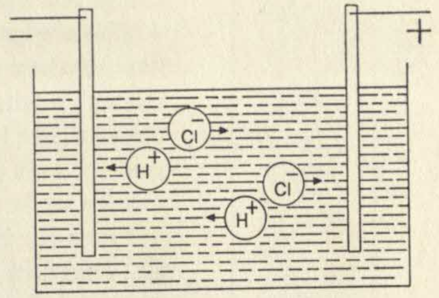

Fig. 3

What happens during electrolysis. Negative ions are attracted to the positive plate, and positive ions are attracted to the negative plate.

When the battery is connected to the plates the chlorine ions are attracted to the positive plate. Since unlike charges attract this shows that chlorine ions are negatively charged. The hydrogen ions are attracted by the negative plate and are therefore positively charged ions. As it takes the same quantity of electricity to liberate 1 atom of hydrogen as it does to liberate 1 atom of chlorine the hydrogen and chlorine ions must carry the same quantity of electricity (that is, the same charge) through the solution. Faraday's term ion for these parts of the substance that travel through the solution now means more explicitly an atom or group of atoms which has an electric charge. The hydrogen and chlorine ions thus carry equal but opposite electric charges. When these ions arrive at the plates their charges are neutralized and atoms of hydrogen and chlorine are produced which no longer carry a charge. The atoms of chlorine then combine in pairs to form molecules and the chlorine is given off as a greenish coloured gas at the positive plate. In a similar way hydrogen is given off at the negative plate.

One way of picturing what happens in electrolysis, then, is this. In hydrochloric acid the charges of the hydrogen and chlorine ions exactly balance each other so that the hydrochloric acid molecules have no resultant charge. Immediately they are dissolved in water the molecules split up into the positively charged hydrogen ions and negatively charged chlorine ions. The action of the water is just to separate the charges already present (but undetectable) in the hydrochloric acid molecules. When the positive and negative plates are put into the solution the ions are attracted to their respective plates and neutral atoms are produced as already described.

The important thing about electrolysis from our point of view is the size of the charge carried by the ions. It was found that ions carried charges of varying size according to the solution. But the charge on any ion was always a multiple of a certain basic charge. If we let this basic charge be represented by the letter *e* then ions with charges like $\frac{1}{2}e$, $\frac{3}{4}e$, $3{\cdot}5e$, or $7{\cdot}63e$ are never found.

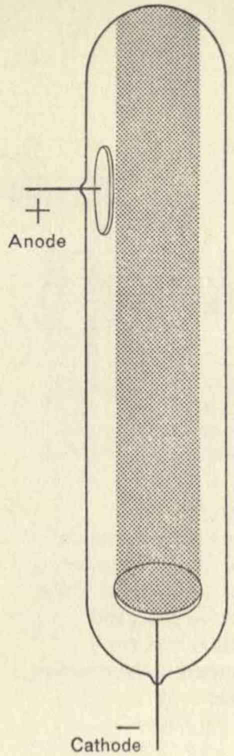

Fig. 4a
A simple discharge tube.

Ions always carry a charge of *e*, 2*e*, 3*e*, 4*e* and so on. No ion ever carried a charge less than *e*, or a fraction of it.

This charge *e* is very small. For example, a current of electricity is just a flow of these charges whether it is through a liquid as in electrolysis or through a wire in a radio set or television receiver. The current through a 60-watt light bulb is about ¼ of an ampere (the unit of electric current). To produce even this quite small current 1 562 500 000 000 000 000 of the basic charges we have called *e* pass through the filament of the bulb every second.

These results suggested still more strongly than Faraday's original work that electricity is atomic in nature, i.e. always occurs in multiples of *e*. And in 1891 G. Johnstone Stoney proposed the name electron for *e*, the basic unit of electric charge as found in electrolysis.

Conduction of electricity through gases

Now if electricity is carried through liquids in multiples of *e* like this, perhaps gases conduct electricity in the same way. Several scientists began to investigate this problem. They found that air under normal atmospheric pressure (76 cm of mercury) will only conduct electricity when a very high voltage is used. For example, when 30 000 volts are applied across a gap of 1 cm between two metal spheres the air becomes highly conductive and a spark passes.

If two metal plates are sealed into a glass tube and then the pressure in the tube is reduced to about 1 mm of mercury the air conducts electricity continuously when a potential difference of several thousand volts is applied across the plates. This is called a continuous discharge and whilst it is taking place the air in the tube gives off a lovely coloured glow. Many applications of this can be seen in the coloured strip-lights used for advertising; the familiar red neon signs are one example. When the pressure is reduced to less than 1/100 of a mm of mercury the glow disappears; the inside of the tube becomes dark but the glass at the far end of the tube from the negative plate glows green (Fig. 4a). These tubes are called discharge tubes. The negative plate is called the cathode and the positive plate is called the anode.

At first it was thought that the rays travelled straight from the cathode to the anode—those which missed the anode struck the glass at that end of the tube and produced the green glow. But it was soon discovered that if the anode was placed at one side, as in Fig. 4a, the rays did not change direction, and the glow was still produced on the end of the tube opposite the cathode. It was also found that if the cathode was made concave the rays were brought to a

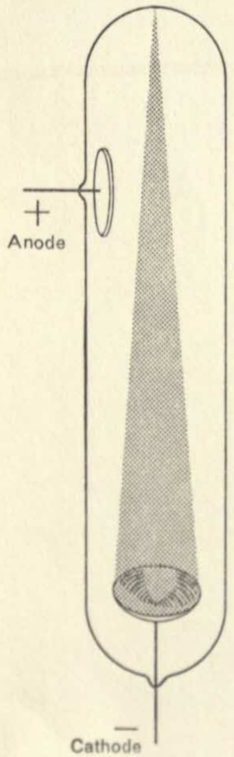

Fig. 4b Concave cathode focuses rays on far end of tube.

focus (Fig. 4b). These experiments indicated that the rays travel perpendicularly away from the surface of the cathode.

A simple experiment (Fig. 5) confirmed that the green glow is produced by rays travelling in straight lines from the cathode. They were consequently called cathode rays.

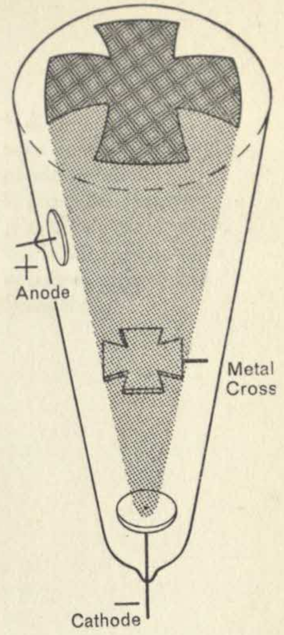

Fig. 5
The sharp shadow of the cross shows that the rays travel in straight lines from the cathode.

The nature of cathode rays

Although several scientists were working with cathode rays it was J. J. Thomson in 1897 who showed that they behaved as streams of negatively charged particles, and that the charge they carried was the same as *e*, the basic charge found in electrolysis.

Before this work of Thomson's there were two views as to the nature of cathode rays: (i) a group of German scientists thought they were a form of radiation, like light waves; (ii) scientists in England, however, thought they were streams of charged particles.

In 1895, J. Perrin in France did an experiment which indicated that cathode rays carried a negative charge, but it was not conclusive.

Now waves are not deflected by electric or magnetic fields, whereas charged particles are deflected by such fields. By the experiment illustrated in Fig. 6 Thomson, working at the Cavendish Laboratory in Cambridge in 1897, confirmed that cathode rays are streams of charged particles. Further, the direction in which the particles were deflected told him that they carried a negative charge.

In order to investigate more thoroughly the properties of these negatively charged particles Thomson had a special discharge tube made, Fig. 7. The anode was a cylinder of metal pierced by a narrow slit, and close to it was another cylinder with a similar narrow slit. This arrangement confined the cathode ray particles to a narrow beam. Therefore, when the pressure of the gas in the tube was reduced and the high voltage applied, a bright green image of the slit appears at P.

Also sealed into the tube were two deflector plates A and B. When Thomson applied a positive potential to B

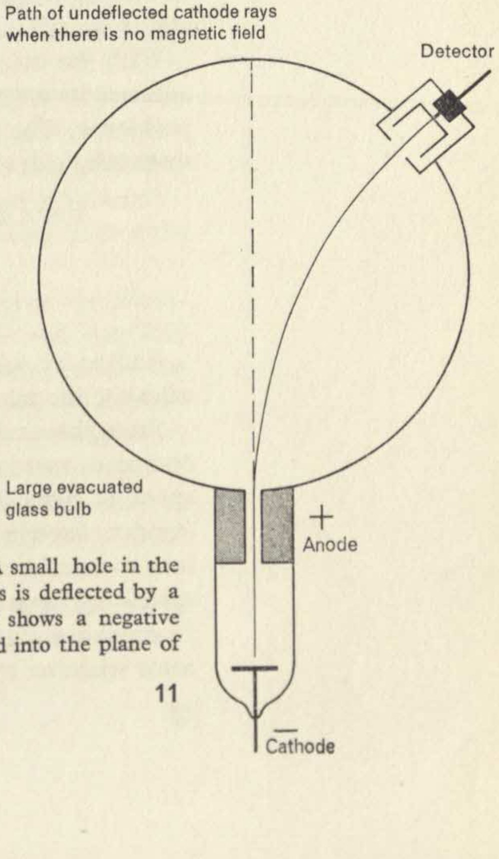
Path of undeflected cathode rays when there is no magnetic field
Detector
Large evacuated glass bulb
+
Anode
—
Cathode

Fig. 6 To show that cathode rays carry a negative charge. A small hole in the anode produces a narrow beam of cathode rays. This is deflected by a magnetic field towards the detector, which at once shows a negative charge. The magnetic field was perpendicular to, and into the plane of the paper.

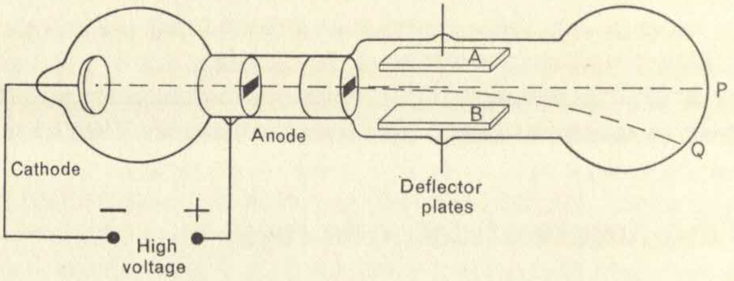

Fig. 7
The discharge tube Thomson used to measure the speed of cathode ray particles v, and *e*/*m* the ratio of the charge they carried to their mass.

the beam was deflected down to Q. As like charges repel and unlike charges attract this again showed that the particles carried a negative charge. When he cut off the electric field the beam reverted back to its original position P.

Thomson was also able to produce a similar deflection by applying a magnetic field at right angles to the electric field.

With the magnetic field alone switched on Thomson measured the radius *r* of the arc into which the beam was deflected. From this he worked out the following equation for the ratio of the charge *e* the particles in the beam carried to their mass *m*:

$$e/m = \frac{v}{Hr} \tag{1}$$

H was the strength of the magnetic field, the experiment gave the value of *r* and so he still had to find v before e/m could be calculated.

With the magnetic field still on Thomson applied the electric field and adjusted its magnitude *E* until he had brought the beam back to its original position P. The forces on the particles in the beam due to the electric and magnetic fields then exactly balanced each other, i.e.:

$$\text{Force due to magnetic field} = \text{Force due to electric field}$$

$$Hev = Ee$$

$$\text{Therefore } v = \frac{E}{H}.$$

And so by substituting this value in equation (1) Thomson was able to calculate the value of e/m for the particles in the beam.

From these calculations he found that the particles were moving with the enormous speed of about 18 600 miles per second—just about a tenth of the speed of light. The value of e/m for these particles was over 1 000 times (modern experiments show it to be 1 840 times) the value of e/m for hydrogen ions as calculated from electrolysis experiments. Thomson also got approximately the same values for v and e/m whatever gas was in the tube. From this he concluded that the 'carriers of the electric charge in the cathode rays are the same whatever the gas through which the discharge passes'. In view of this he said it seemed likely that all gases contained the negatively charged particles found in cathode rays. Since the elements present in gases are present in solids and liquids it also seemed likely that all matter contained these negatively charged particles.

The electron

This idea was so important that Thomson hastened to learn more about these negatively charged particles. In particular he wanted to know why he had obtained such a high value for e/m. There were three possible explanations.

(i) The cathode ray particles and the hydrogen ion have the same mass but the charge on the cathode ray particles is 1 840 times that on the hydrogen ion.
(ii) The charges are the same and the mass of the cathode ray particles is 1 840 times smaller than that of the hydrogen ion (and hydrogen is the lightest known element).
(iii) Both the mass and the charge are different.

In 1899 Thomson decided that (ii) was correct by measuring the actual charge e as well as e/m. Unfortunately he could not devise an experiment to do this for the cathode ray particles themselves. Instead he found that the negatively charged particles which are produced when ultraviolet light falls on zinc (called the photoelectric effect, since an electric current is produced by the action of light), and also those emitted from a hot wire (called the thermionic effect because the negatively charged particles, i.e. ions are produced by heat) gave exactly the same value for e/m as he had obtained in his experiments on cathode rays. He therefore concluded that even though they were produced in such different ways the particles were identical.

He was able to devise an experiment to measure the charge on the photoelectric particles. This experiment was rather complicated and not very accurate. What it did show was that the photoelectric particles carried the same charge as the hydrogen ion in electrolysis, that is, the charge Stoney had christened the electron. Since the negatively charged particles in cathode rays and in the thermionic effect behaved in the same way as the photoelectric particles and had the same value of e/m Thomson concluded that they all carried the same charge. As this charge was called the electron the particles themselves soon became known as electrons.

By substituting this value of e in the previously measured value of e/m the value of m was calculated. Thomson found that it was over 1 000 times less than the mass of the hydrogen atom.

As Thomson pointed out, hydrogen atoms were the lightest † known particles at that time. The fact that electrons were so much lighter than hydrogen atoms, and that they could be produced in different ways—by an electric discharge through different gases and by the thermionic and photoelectric effects—strengthened his idea that they were probably present in all matter.

The actual value of e, in coulombs, is 1·601 divided by 10 million million million, a very small quantity indeed. So that we don't have to keep writing it out and since electric charges are always a whole number times e it is convenient always to use the symbol e for the electronic charge. *We can therefore define an electron as a particle with a mass equal to 1/1 840 times the mass of a hydrogen atom, and which carries a negative charge of e.*

Thomson's idea that the atoms of all elements contained electrons was further strengthened by the fact that it explained some surprising experimental results.

In 1886 Goldstein discovered that when he used a perforated metal disc as the cathode in a discharge tube visible rays appeared on the side of the cathode remote from the anode (Fig. 8). These rays emerged in straight lines from the holes in the cathode. Nine years later in 1895 Perrin showed that the rays carried a positive charge by an experiment similar to the one illustrated in Fig. 6. As a result of this they were called positive rays. It was not until 1913 however that the nature of positive rays was finally understood.

Then, in order to investigate these positive rays more thoroughly Thomson constructed the apparatus shown in Fig. 9. He used it to measure the value of e/m for the positive rays by deflection experiments similar to the ones he had already used for cathode rays. The results of these experiments showed that e/m was different for positive rays from different gases. He also found that

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† The weight of a body is the force which gravity exerts on the mass. The mass is a property of the body which does not change. If you were to go to the moon your mass would remain the same but your weight would be reduced since the force of gravity is less on the moon than it is on the earth.

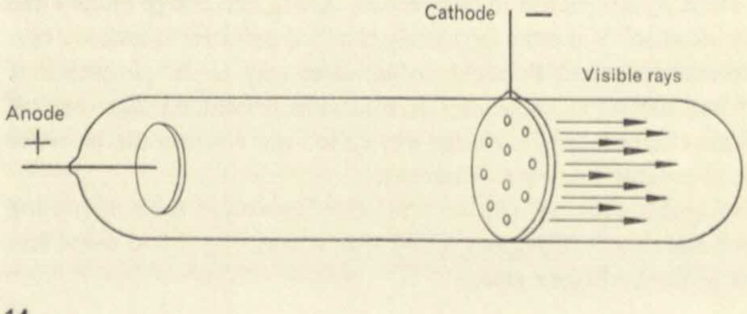


Fig. 8
Goldstein's experiment with a perforated cathode.

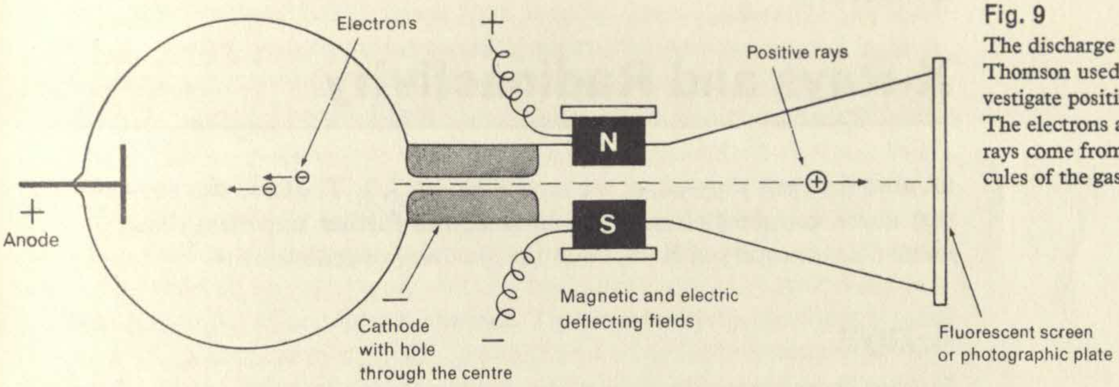


Fig. 9
The discharge tube Thomson used to investigate positive rays. The electrons and positive rays come from the molecules of the gas in the tube.

with hydrogen in the discharge tube the positive particles were almost as heavy as hydrogen atoms. Similarly, with oxygen in the tube the positive particles were almost as heavy as oxygen atoms. It looked as if the positive particles were atoms of the gas minus an electron. On this assumption Thomson said that ordinary neutral atoms contained an equal number of positive and negative charges (Fig. 10). When such an atom loses an electron it leaves behind a positively charged ion. This clearly explained the production of cathode rays and positive rays.

Thomson did not try to explain why a neutral atom should lose an electron in the production of cathode and positive rays. By assuming that it did happen he was able to explain the experimental observations, and so the assumption was a valid one. If in the future we come across observations which indicate that neutral atoms do not lose electrons in these circumstances then we must discard this idea and find one that will explain the new observations.

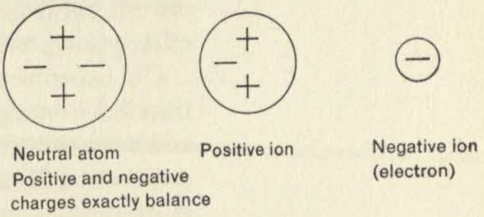


Fig. 10
Thomson's picture of an atom.

These assumptions we make in science are really just guesses. But they are guesses based on the results of experiments, and it is the experimental results which determine whether our guesses are correct or not.

Thomson's work had shown that electrons existed and that they were lighter than the lightest known atom, hydrogen. This was a revolutionary discovery. For centuries atoms had been regarded as tiny marbles—solid and indivisible. Yet here was a particle, the electron, which apparently came from all atoms. A whole new world of scientific study was opening up, and the years 1895 to 1915 produced many more startling discoveries as we shall see in the next chapter.

Chapter 4

X-Rays and Radioactivity

DURING the years 1895–98, at the same time that J. J. Thomson was showing that atoms contained electrons, there were two further important developments: the discovery of X-rays and the discovery of radioactivity.

X-rays

In 1895 X-rays were discovered almost by accident. A German physicist, Röntgen, was experimenting with a discharge tube similar to the ones used to produce cathode rays. For some reason, nobody knows quite why, he covered the tube with black cardboard. The discharge tube was completely covered so that the green glow where the cathode rays struck the glass could not be seen. Röntgen noticed that a sheet of paper coated with barium platinocyanide which he had used in another experiment and was lying nearby, glowed brightly—but only when the discharge tube was on. Something was penetrating the cardboard screen. Actually William Crookes had noticed a similar effect years previously but had not considered it important.

On experimenting further Röntgen found that these penetrating rays travelled in straight lines and would pass through several centimetres of wood and even thin sheets of aluminium. Not knowing what they were Röntgen called them X-rays. The more perfect the vacuum in the discharge tube the more penetrating were the X-rays. Röntgen also found that while the rays would penetrate flesh, they were stopped by bones. Very soon X-rays were being used in hospitals to detect bone fractures.

The nature of X-rays

Until 1912 the nature of X-rays was unknown. Just as with cathode rays some scientists believed that X-rays were waves, others believed that they were particles.

When a stream of particles (like the electrons in cathode rays) meets an obstacle a sharp shadow is formed, just as in the cathode ray experiment illustrated in Fig. 5 on p. 11. Now if a wave meets an obstacle it does not give a sharp shadow; it is able to bend round the obstacle to some extent. The longer the wavelength the more it bends round the obstacle and the less sharp is the shadow. This bending of waves round an obstacle is called diffraction. Sound waves are diffracted and it is easy to hear round corners. But you cannot see round corners. Light waves seem to give sharp shadows. If you look closely enough, however, using special apparatus and a microscope, it becomes clear that light waves too are diffracted. The diffraction of light is much smaller than that of sound because light waves have a much shorter wavelength than sound waves. Diffraction is only observed when the obstacle is of a similar size to the wavelength.

The principal way in which the diffraction of light waves is shown is by using a diffraction grating. A diffraction grating is a series of lines ruled very closely together on glass or on a piece of transparent plastic. A typical diffraction grating has 15 000 lines to the inch. The lines are opaque to the light and so form an obstacle to its path. The thickness of the lines is obviously very small—of the order of the wavelength of the light being used—and so the light is diffracted.

Early attempts to diffract X-rays with the most closely ruled gratings were unsuccessful. In 1912 however von Laue at the University of Munich had the idea that crystals, with their regularly spaced atoms, might act as gratings and produce diffraction with X-rays. When this experiment was tried it was found that the X-rays were diffracted, thus showing that they were waves.

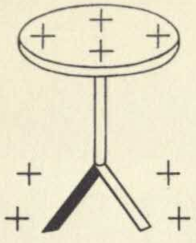
In 1913 Sir William Bragg and his son, now Sir Lawrence Bragg, developed this method of X-ray diffraction and measured their wavelength. They found that the wavelengths of X-rays were about 1/100 000 000 of a cm—much smaller than the wavelength of visible light.

Used indiscriminately X-rays can cause damage, and the hands of many early workers were deformed because of their continual exposure to the rays. Used carefully X-rays have become indispensable in medicine, industry, and research.

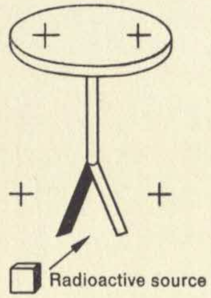
But how is it that they are able to travel through certain thicknesses of different solids? It was the discovery of radioactivity which led to the answer to this question, and which also gave scientists a much clearer picture of what atoms are like.

Radioactivity

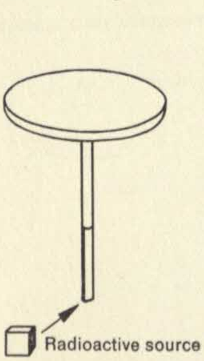
In 1896 a Frenchman, Becquerel, was investigating the action of sunlight on a large crystal of potassium uranyl sulphate, a compound which contained uranium. He carefully wrapped a photographic plate in black paper so that no sunlight could get in, placed the crystal on top of the covered plate and left it in sunlight for some time. When he developed the plate he found that the crystal had left an image of itself. Clearly some sort of radiation from the crystal had penetrated the black paper to produce the image. At first Becquerel thought that this radiation was produced by the action of the sunlight on the



Electroscope charged, gold leaves move apart



Rays from the source ionize the air and the leaves move together



All the charges on the electroscope have been neutralized. The leaves hang vertically downwards.

Fig. 11
Gold leaf electroscope. The case protecting the leaves from draughts has been omitted for simplicity.

uranium. But one day, when he had wrapped a fresh photographic plate in black paper in preparation for a further experiment, the sun went in: so he left his experiment and put the covered plate with the crystal on top of it in a drawer. A few days later he developed the plate, expecting to find little or no image. To his amazement the image was just as intense as before. The radiations were obviously coming from the crystal itself; sunlight had no effect.

It was soon discovered by Marie and Pierre Curie and others that the elements radium, polonium, thorium, and actinium also produced such radiations. In 1898 Marie Curie called this effect radioactivity.

The radioactivity of uranium compounds was investigated by Ernest Rutherford, a New Zealander working at the Cavendish Laboratory in Cambridge. He did this by measuring the amount of ionization the rays produced in a gas: that is, by the extent to which the rays were able to split the neutral gas molecules into negatively and positively charged ions. In this way air, which is normally an insulator, can be made to conduct electricity.

This ionization effect of the rays from radioactivity was discovered by the use of an electroscope. An electroscope consists of a brass plate connected by a rod of the same material to two gold leaves which hang vertically downwards as shown in Fig. 11. The delicate gold leaves are protected from draughts by a glass case. When a positive charge is put on the top plate it spreads over all the metal, since brass conducts electricity. This means that both gold leaves now have a positive charge. Like charges repel each other and so the leaves move apart.

When a radioactive substance is placed near such a charged electroscope the leaves slowly move together again. This is because the rays from the radioactive substance ionize the air: they split the neutral air molecules into negatively and positively charged ions (Fig. 12). If the charge on the leaves is positive the leaves attract the negative ions in the air. When the ions reach the leaves they neutralize the positive charges. The leaves have no charge and so hang vertically downwards again. The stronger the rays from the radioactive substance the more ions are produced. If there are a large number of ions the charge on the leaves is neutralized quickly and so the leaves go together quickly; if there are few ions it takes longer for the charge to be neutralized and so the leaves go together slowly. Thus the rate at which the leaves go together tells us the amount of ionization and hence the strength of the rays emitted by the radioactive substance.

Using such an electroscope Rutherford discovered that the amount of ionization close to the surface of a uranium compound was much greater than it was a few centimetres away. He explained this by saying that the rays must be of at least two types: those which could only penetrate a few centimetres of air; and those which could penetrate much further into the air.

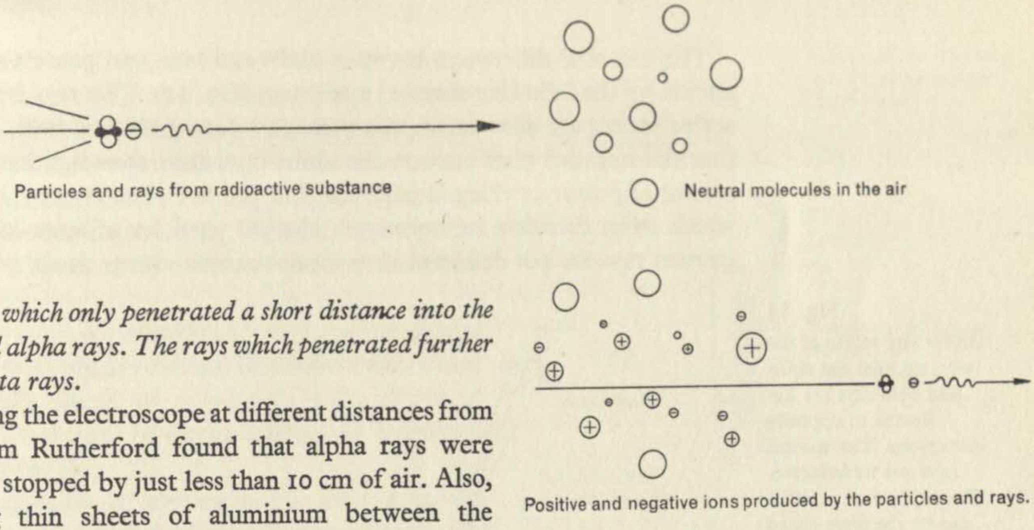

Particles and rays from radioactive substance
Neutral molecules in the air
Positive and negative ions produced by the particles and rays.

Fig. 12
Ionization.

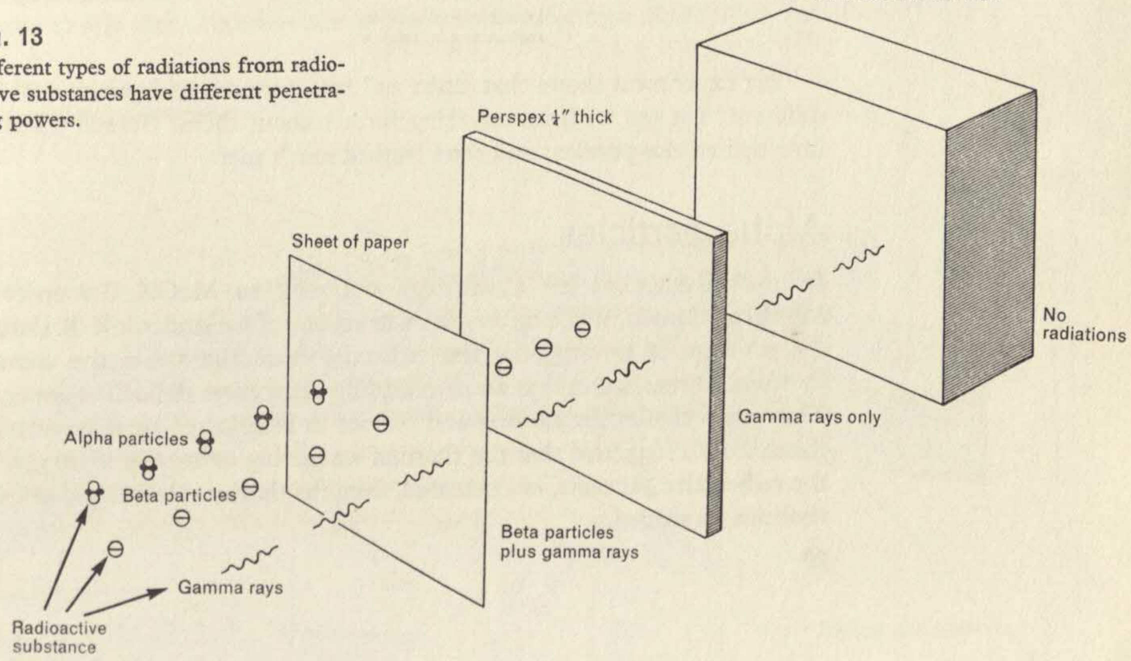
The rays which only penetrated a short distance into the air he called alpha rays. The rays which penetrated further he called beta rays.

By placing the electroscope at different distances from the uranium Rutherford found that alpha rays were completely stopped by just less than 10 cm of air. Also, by placing thin sheets of aluminium between the uranium and the electroscope he found that alpha rays are stopped by aluminium 0·002 cm thick.

In the same sort of way he found that the penetrating power of beta rays is roughly 100 times that of alpha rays.

In 1900 shortly after these discoveries by Rutherford, a Frenchman, Villard, found that a third type of ray, later called gamma rays, were also emitted from radioactive substances. These gamma rays were much more penetrating than even beta rays. The gamma rays from some radioactive substances can be detected through iron 30 cm thick. Fig. 13 shows how different substances can stop different kinds of radiation.

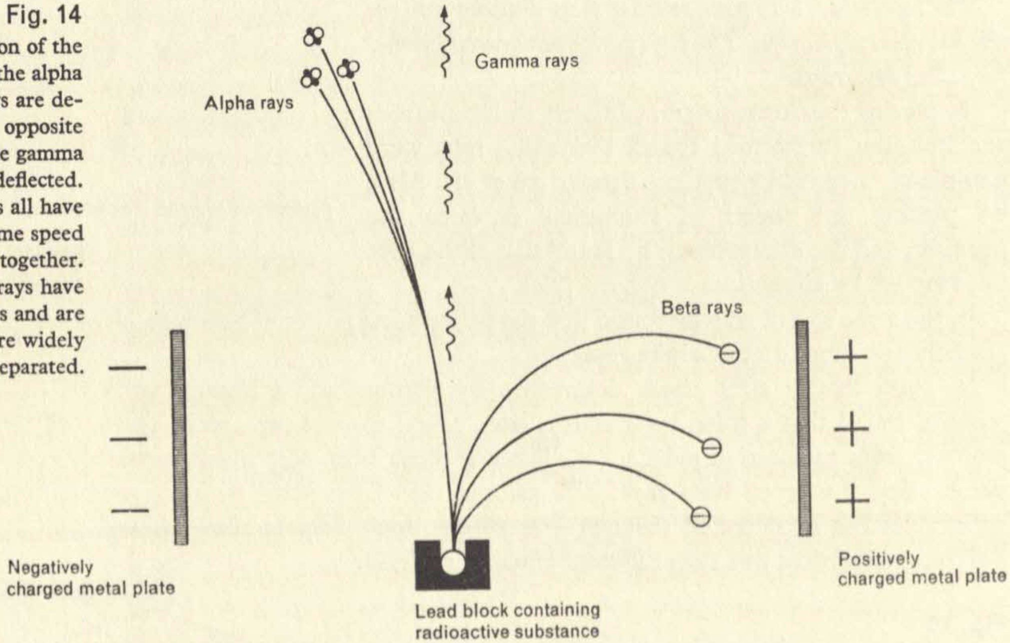
Fig. 13
Different types of radiations from radioactive substances have different penetrating powers.



The essential differences between alpha and beta and gamma rays can be shown by the following simple experiment (Fig. 14). The rays from a radioactive source are allowed to pass through a strong electric field. It is found that the negative plate attracts the alpha rays, thus showing that they must consist of positively charged particles. The positive plate attracts the beta rays which must therefore be negatively charged particles of some kind. As the gamma rays are not deflected they cannot carry a charge at all.

Fig. 14

Under the action of the electric field the alpha and beta rays are deflected in opposite directions. The gamma rays are undeflected. The alpha rays all have nearly the same speed and so travel together. The beta rays have different speeds and are therefore widely separated.


Gamma rays
Alpha rays
Beta rays
—
—
—
+
+
+
Negatively charged metal plate
Positively charged metal plate
Lead block containing radioactive substance

This experiment shows that alpha and beta particles and gamma rays are different; but can we learn anything further about them? Several scientists investigated this problem and soon learned much more.

Alpha particles

In 1898 Rutherford left Cambridge and went to McGill University in Montreal, Canada. While he was there he set one of his students R. B. Owens, the problem of investigating the radiations from the radioactive element thorium. Owens found that these radiations were most difficult to measure. They were continually varying and seemed to be affected by movements in the air. This suggested that the thorium was giving off a radioactive gas. As the radioactive gas came, or emanated, from the thorium Rutherford called it thorium emanation.

Radium was also found to give off a similar emanation. Both thorium and radium emanation are radioactive. The radiation emitted by both these emanations only penetrated a short distance in air and so the emanations must themselves emit alpha particles. Using an electroscope he could not detect any other more penetrating radiations and so the emanations must emit alpha particles only.

From deflection experiments to measure the charge and *e*/*m* for these alpha particles Rutherford concluded that they had a charge of 2*e* (where *e* is the charge of the electron) and were of mass 4 (taking the hydrogen atom as of mass 1).

The atomic mass of helium is just over 4 so the simplest explanation of Rutherford's experiment was that alpha particles were neutral helium atoms which had lost 2 electrons. By losing 2 electrons the ion left had a positive charge of 2*e* and its mass was only very slightly smaller since the mass of an electron is only 1/1 840 times the mass of the hydrogen atom.

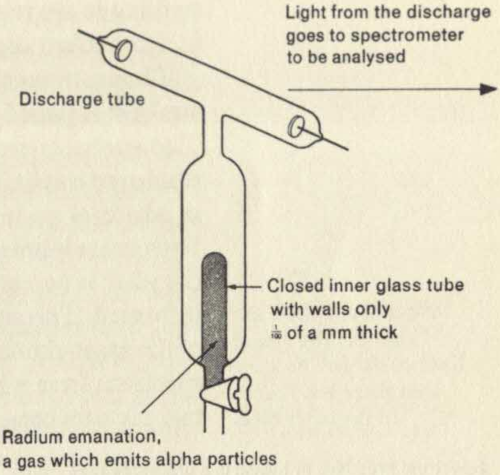
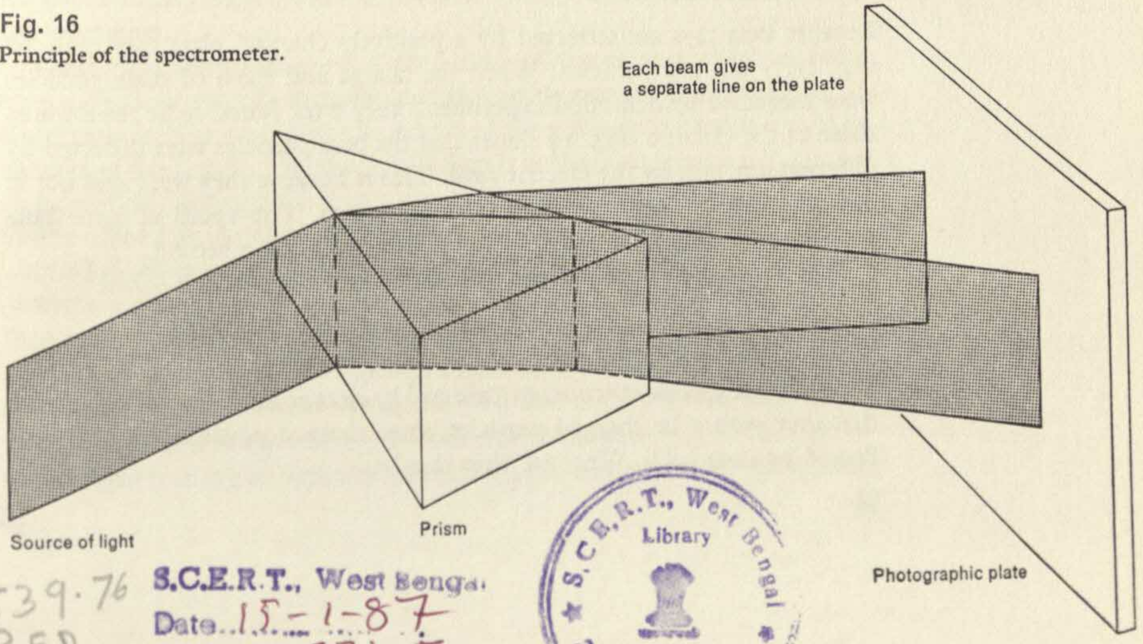

Light from the discharge goes to spectrometer to be analysed
Discharge tube
Closed inner glass tube with walls only $\frac{1}{100}$ of a mm thick
Radium emanation, a gas which emits alpha particles

Fig. 15
Rutherford's experiment to show that alpha particles are parts of helium atoms.

This explanation was soon confirmed by Rutherford using the apparatus shown in Fig. 15. Radium emanation, which emits alpha particles only, was placed in the inner glass tube. This tube had very thin walls so that the alpha particles could get through it. The air in the outer vessel was then pumped out. After the apparatus had been left for a few days an electric discharge was passed through this outer tube. The light emitted by the discharge was analysed and showed clearly that there was now helium in the outer tube. Since there was

Fig. 16
Principle of the spectrometer.



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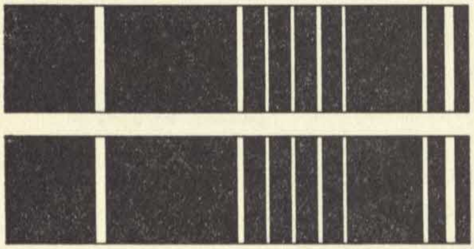
nothing in the tube before, and only alpha particles had been able to get into it, Rutherford concluded that alpha particles are parts of helium atoms.

The instrument used to analyse the light is called a spectrometer. When sunlight is passed through a prism it splits up into the colours of the rainbow. The spectrometer works in exactly the same way. Light from an electrical discharge is split into separate beams by a prism. The light from each element in whatever gas is in the discharge tube is split up into different sets of beams. Each beam is brought to a sharp focus on a photographic plate (Fig. 16). When the plate is developed a series of lines corresponding to the different elements is formed. This series of lines is called the spectrum of the gas. The spectrum of the gas in the outer tube in Rutherford's experiment was compared with the spectrum from a tube specially filled with helium (Fig. 17). The lines in the two pictures corresponded, showing that there was helium in the outer tube.

Fig. 17
When Rutherford saw that the two sets of lines coincided, he knew that there was helium in the outer tube.

Spectrum produced by helium in a discharge tube



Spectrum similar to the one obtained in Rutherford's experiment

This method of spectrum analysis is widely used in research laboratories for the detection of elements, especially when the element is only likely to be present in small amounts.

The experiments described above showed that alpha particles have a positive charge of 2e and a mass of 4, and that helium atoms consist of an alpha particle plus 2 electrons. The results of deflection experiments also showed that alpha particles emitted by radioactive substances travel very fast—about 8 500 to 12 800 miles a second, and that all the alpha particles from a particular source have approximately the same speed.

Beta particles

Because beta rays are attracted by a positively charged plate they must be negatively charged particles. When the charge and mass of these particles were measured by deflection experiments they were found to be the same as those of the electron. Fig. 14 shows that the beta particles were deflected by different amounts by the electric field. This is because they were shot out at different speeds from the radioactive substance. The speed of some beta particles approaches the speed of light—186 000 miles a second.

Beta particles are thus electrons travelling at very high speeds indeed.

Gamma rays

The fact that gamma rays are not deflected by electric or magnetic fields shows that they cannot be charged particles, since charged particles would be deflected by such fields. What are they then?

This question was not answered conclusively for some 14 years. Then, in 1914, it was shown that gamma rays are waves, like light waves but with an extremely short wavelength, similar to very short wavelength X-rays. This was done in the following way.

Because gamma rays were undeflected by electric and magnetic fields it was thought that they might be waves. If they are waves they should show diffraction. At first this diffraction could not be found. Then, in 1914 Rutherford and Andrade performed an experiment similar to the one Sir William Bragg and his son used for X-rays and they found that gamma rays too were diffracted by the regularly spaced atoms in a crystal. The obstacles used previously must have been too large. By taking careful readings in their experiment they were able to measure the wavelength of the gamma rays and found it to be extremely small indeed—only about 1 ten thousand millionth of a centimetre. *Gamma rays are thus waves which have an extremely short wavelength.*

The nature of radioactivity

Not all radioactive elements necessarily emit alpha and beta particles and gamma rays simultaneously. Some emit just alpha particles; others both alpha and beta particles; others beta particles and gamma rays; and yet others just gamma rays.

In 1902 Rutherford and Soddy put forward an explanation or theory of what happened in radioactivity. They had found that thorium did not produce the radioactive gas thorium emanation directly, but that an intermediate form of thorium was first produced. Rutherford and Soddy called this form of thorium, thorium X. They were able to separate thorium X from thorium by a simple chemical process, and they found it was the thorium X which gave off the emanation.

These facts were explained if the atoms of the original thorium spontaneously disintegrated, throwing out part of themselves in the form of an alpha particle. The atom that was left after losing the alpha particle would be an atom of thorium X. The thorium X then spontaneously shoots out another alpha particle, leaving behind an atom of thorium emanation. Rutherford and Soddy called this the disintegration theory of radioactivity.

The idea of atoms spontaneously disintegrating and becoming atoms of a different element was so new that many scientists strongly criticized it. Rutherford replied to these criticisms by explaining what a scientific theory really is. A theory is an attempt to explain the results of experiments and arising out of this it should suggest new experiments to try. As long as the theory does this it is a good one. But when the observations from the experiments begin to disagree with the theory, then the theory must be changed to fit the facts. 'In these respects,' said Rutherford, 'the disintegration theory, whether or not it may ultimately be proved correct, has already been justified by its results.'

Subsequent experiments have, in fact, borne out the correctness of Rutherford and Soddy's disintegration theory of radioactivity.

When a radioactive atom disintegrates it is said to decay. When radium decays by shooting out an alpha particle a radioactive gas, radon, is produced. Radon itself decays by emitting an alpha particle to produce a form of the element polonium. This process goes on, sometimes by the emission of a beta particle instead of an alpha particle and sometimes by the emission of both until the radium we started with has been converted into a form of lead which is not radioactive. Every radioactive element decays in a similar way, the process stopping when the emission of an alpha or beta particle results in a stable form of element. As an example here are the first two changes in the decay of radium.

Radium	—	Alpha particle	⟶	Radon
mass 226		mass 4		mass 222
charge 88		charge 2		charge 86

Radon	—	Alpha particle	⟶	Polonium
mass 222		mass 4		mass 218
charge 86		charge 2		charge 84

After nine more decay processes the element thallium is formed and this decays in the following way to produce a stable form of lead.

Thallium	—	Beta particle	⟶	Lead (stable)
mass 206		mass negligible		mass 206
charge 78		charge − 1		charge 79

In the first of the above changes we can see that the radon produced should have a mass of 222. After difficult experiments Ramsey confirmed that this was correct. The experiment was difficult because there were only small quantities of radon and it is radioactive.

Half-life

As we have seen, an atom which sends out a particle during radioactivity becomes an atom of a different element. In some cases this decay process is very slow, in others it is very fast.

The spontaneous disintegration of atoms in this decay process is entirely random: there is no means of telling which particular atom is going to disintegrate next. If instead of looking at individual atoms we look at the substance as a whole it is found that half the atoms present at a given instant disintegrate after a certain time. For radium this time is 1 590 years. This means that if we start with 20 grams of radium now, in 1 590 years there will be 10 grams of it left. Another 1 590 years later still there will be only 5 of the original 20 grams of radium left. *The 1 590 years is the time it takes for half the radium atoms present at any time to disintegrate. This time is therefore called the half-life of the element.* The half-life of actinium is 20 years (Fig. 18), the half-life of radon is just less than 4 days, while the half-life of polonium (mass 216) is only 0·16 of a second.

The half-life of a radioactive element clearly measures the speed at which the decay process takes place. Attempts to speed the process up (or slow it down) by heating, increasing the pressure or adding chemical reagents have all failed. The half-life is a characteristic of each radioactive element and is independent of all other factors.

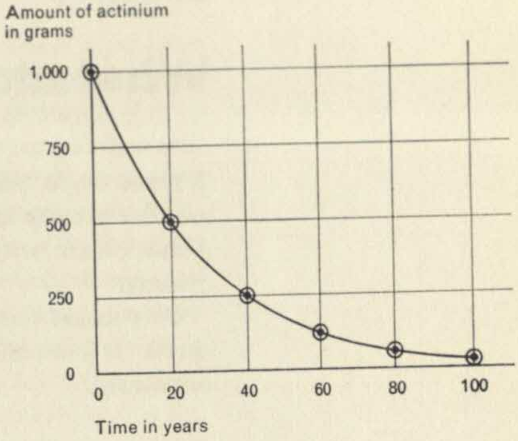


Fig. 18

Half-life. Actinium has a half-life of 20 years. The graph shows the amount of actinium present at any given time. After each period of 20 years half the atoms present at the beginning of that 20 years have decayed.

Artificial radioactivity

All the elements which are naturally radioactive have high atomic masses, viz.: uranium 235, radium 226, &c. It seems that the very heaviness of the atoms makes them unstable so that they hurl out alpha and beta particles and gamma rays. In 1934, however, it was found that even elements which had light atoms could be made radioactive in the laboratory. This was done by bombarding the atoms of the light element with alpha particles from a naturally radioactive element. The light element then became radioactive. For example, when aluminium is bombarded by alpha particles a radioactive form of phosphorus is produced. Radioactivity produced in the laboratory like this is called artificial radioactivity. It is of immense practical and theoretical importance, as we shall see later.

There is one further point to note about radioactivity. Since radioactive atoms shoot out electrons, alpha particles and gamma rays at very high speed they must themselves be the source of considerable stores of energy.

Chapter 5

What atoms are like

WE now know quite a lot about how radioactive atoms behave. But what are they actually like? Can we draw a picture or make a model of an atom? Atoms cannot be seen, and all we know about them has been discovered indirectly.

This means that any picture or model is likely to be wrong in some respects. It must therefore be changed to fit in with new facts as they are discovered.

Thomson's picture of the atom

We saw in Chapter 3 how Thomson arrived at his picture of a neutral atom as an equal number of positive and negative charges. Take the simplest element, hydrogen. Discharge tube experiments with different gases showed that the positive particles left when an electron was removed from the neutral atom of hydrogen, was the lightest of them all. In 1920 Rutherford, among others, suggested the name proton for this particle. Proton comes from the Greek word protos, meaning first. On Thomson's theory an atom of hydrogen is just a proton and an electron. Since the atom as a whole is electrically neutral and the electron has a charge of $-e$, the proton must have a charge of $+e$. The mass of the hydrogen atom is 1 (even on the new C^{12} scale of atomic masses, hydrogen is still very nearly 1 unit, the difference only being important in very accurate experiments). Because electrons have a very small mass, only 1/1 840 of the mass of the whole hydrogen atom, the mass of the proton can be taken as 1.

A proton is therefore a particle having a charge of $+e$ and of mass 1.

We have also seen that alpha particles are parts of helium atoms which have a mass of 4 and a charge of $+2e$. On Thomson's theory we can picture a neutral helium atom as 2 protons plus 2 electrons. Fig. 19 shows Thomson's picture of the atom of hydrogen and helium. In the picture of the helium atom the charges of the 2 electrons will just balance the charges of the 2 protons, but the atom will only have a mass of 2 from the protons. But since alpha particles have a mass of 4 the neutral atom must also have a mass of at least 4. Thomson's theory only gives it a mass of 2, and therefore does not explain the facts. The facts remained unexplained for some 30 years. During this time many new discoveries were made and the meaning of earlier discoveries became more clearly understood.

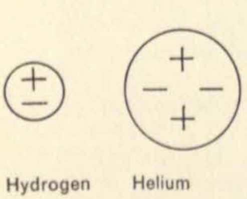


Fig. 19
Thomson's picture of an atom as a sphere with the charges distributed evenly throughout.

Rutherford and the nuclear atom

In 1907 Rutherford returned from Canada to become professor of physics at Manchester University and to continue his study of alpha particles.

From the work already done it seemed clear that if atoms were solid spheres, like marbles, and were packed close together, electrons and alpha particles and the X-rays discussed in Chapter 4 could not possibly get through even a thin sheet of metal. But X-rays, electrons in the form of beta particles and alpha particles do pass through such thin sheets. In an attempt to find out how, two of Rutherford's research workers, Geiger and Marsden, directed a narrow beam of alpha particles at a piece of thin gold foil. The apparatus they used is shown in Fig. 20.

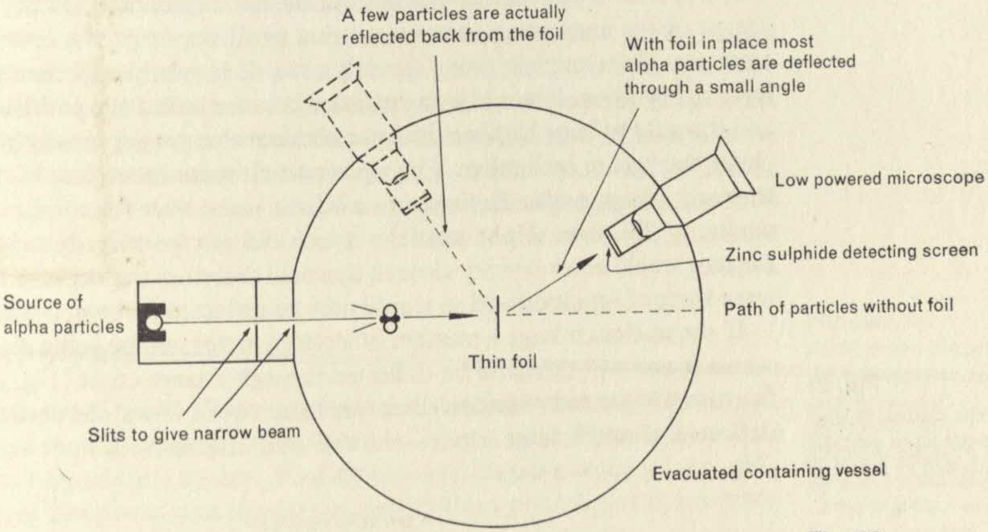

A few particles are actually reflected back from the foil
With foil in place most alpha particles are deflected through a small angle
Low powered microscope
Zinc sulphide detecting screen
Source of alpha particles
Path of particles without foil
Thin foil
Slits to give narrow beam
Evacuated containing vessel

Fig. 20

Geiger and Marsden's experiment to investigate the scattering of alpha particles. Even with the microscope and zinc sulphide screen in the dotted position some reflected particles were detected.

After passing through the foil the alpha particles were detected by the use of a screen coated with zinc sulphide. Each single alpha particle which strikes the screen produces a tiny flash of light which can be seen with a low powered microscope. The experiment was done in a vacuum so that there would be no air molecules for the alpha particles to bump against and be deflected. Without the foil the flashes were seen to form a tiny circle. When the gold foil was placed between the source of alpha particles and the screen the flashes were seen over a much larger area. Some of the alpha particles had been deflected from their original direction. This spreading out of the beam when it passes through the foil is called scattering.

This experiment took place in 1909, and in a similar one using platinum foil, Geiger and Marsden found that on average 1 in 8 000 alpha particles were turned though an angle of more than 90°, that is, were reflected. 'It was as if,' said Rutherford, 'a 15-inch shell had bounced back from a sheet of tissue paper and hit you.'

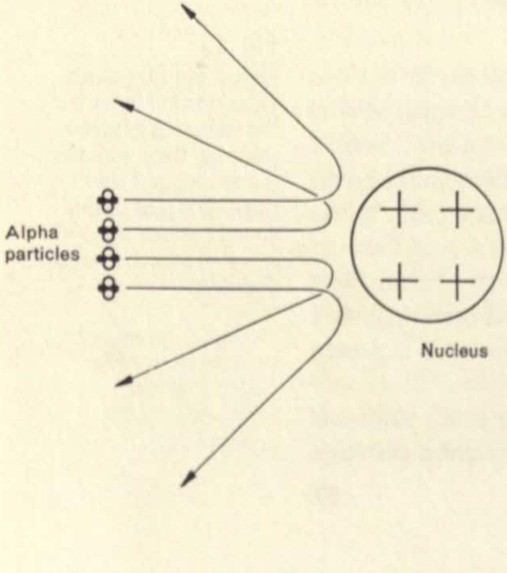
How could these results be explained? On Thomson's picture of the atom the positive and negative charges were evenly distributed throughout the space the atom occupied. When an alpha particle approaches such an atom it would be repelled by the positive charges on the protons in the atom. This explains how scattering occurs. But it does not explain why some of the alpha particles in Geiger and Marsden's experiment were turned through angles greater than 90°. Calculations showed that because the charges are evenly distributed the scattering should only have been slight. Thomson's picture did not fit the facts and therefore had to be modified.

It was over a year before Rutherford hit on the solution. If the positive charge of the atom was concentrated in a small region at the centre of the atom any alpha particle going directly towards it would experience a large force of repulsion. It would be a repulsion because both have positive charges and it would be large because the force between charges get rapidly bigger the closer they get to each other. The alpha particle would therefore be deflected through a large angle. *Rutherford called the concentrated positive charge the nucleus of the atom.* Alpha particles which did not go directly towards the nucleus would never be very close to it, would therefore not experience such a large force of repulsion and so would only be deflected through a small angle.

If the nucleus is large a number of alpha particles will be going directly towards it and will therefore be deflected through a large angle (Fig. 21). The fact that Geiger and Marsden discovered that only a few alpha particles were deflected through large angles showed that the nucleus was very small (Fig. 22).

Fig. 21

If the nucleus is large many alpha particles should be reflected.



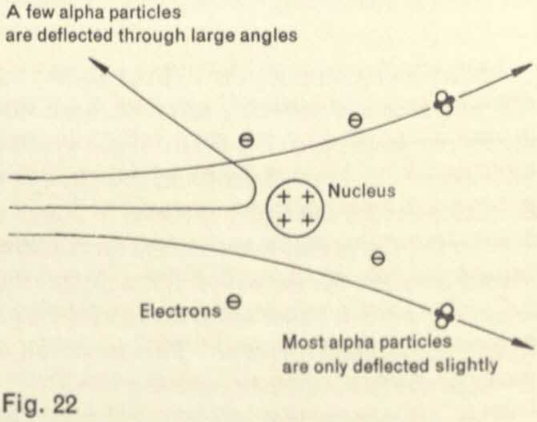

A few alpha particles are deflected through large angles
Nucleus
Electrons
Most alpha particles are only deflected slightly

Fig. 22

A picture of Rutherford's interpretation of the scattering experiments.

What about the electrons in the atom? The positively charged nucleus will attract the negatively charged electrons. Why then do they not fall into the nucleus? Rutherford suggested that the electrons were whizzing round the nucleus all the time. When anything is whizzing round like this there has to be a force acting towards the centre: for example, when a stone securely fastened to the end of a rope is whirled round, the stone would go straight on if it were not pulled in by the rope. In the atom this force is provided by the attraction of the nucleus for the electrons. The electrons move round the nucleus in orbits rather like the orbits of the planets round the sun.

From this picture of the atom as a central nucleus with orbiting electrons Rutherford calculated exactly how alpha particles should be scattered by different thicknesses of various foils. His predictions were completely verified by experiments, showing that his original idea was correct.

Compared with the size of the atom as a whole the nucleus is very small. If the nucleus is represented by this dot · the electrons, drawn on the same scale, would be one and a half times the length of a cricket pitch away. Thus atoms are mainly empty space. It is not so surprising after all that X-rays, electrons, and alpha particles can pass through various thicknesses of solids.

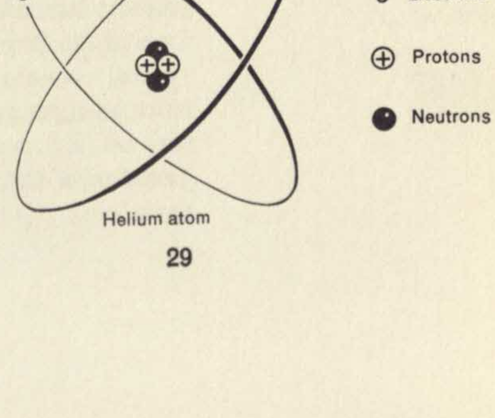
Practically all the mass of an atom is concentrated in the nucleus. So much so, that if you could pack nuclei without any electrons into a pin head it would weigh 100 000 tons.

The neutron

From their experiments Geiger and Marsden were also able to show that the number of positive charges on the nucleus is equal to half the mass of the atom. For example, the nucleus of an atom of helium has a charge of $+2e$ and a mass of 4. The positive charges are carried by the 2 protons, so this accounts for 2 of the units of mass. But what of the other 2 mass units?

Fig. 23

Rutherford's picture of the helium atom. The nucleus consists of two protons and two neutrons, giving it a mass of 4 units and a charge of plus 2 units. To make the atom neutral these are balanced by two circling electrons.



Rutherford suggested that there was another type of particle in the nucleus which had a mass of 1 but carried no positive or negative charge—it was electrically neutral. Thus the helium nucleus might have 2 protons and 2 of these neutral particles to give it a mass of 4 and charge of $+2e$ as found by experiment. The helium atom could then be pictured as in Fig. 23.

Confirmation of Rutherford's theory came 12 years later and the neutral particles were called neutrons. *A neutron is a particle of mass 1 which has no electric charge.* During these years many people used alpha particles to bombard different elements. Irene Joliot-Curie (the daughter of Marie Curie) and her husband, F. Joliot, found that when beryllium was bombarded with alpha particles a very penetrating radiation was emitted. When they tried to absorb these penetrating rays with paraffin wax, instead of being reduced, the intensity of the radiation was actually increased. They found that the increased intensity was due to protons which had been knocked out of the paraffin wax by the penetrating rays. They thought that the protons were knocked out of the paraffin wax by very high energy gamma rays.

In 1932 after carefully repeating these experiments in England, Chadwick showed that such high energy gamma rays could not possibly be produced when beryllium is bombarded by alpha particles. Chadwick therefore discarded this idea. He had however read about Rutherford's idea of a neutral particle. This set him thinking and he calculated that if the alpha particles knocked neutrons out of the beryllium then the neutrons would have enough energy to knock protons out of the paraffin wax. Thus the difficulties in interpreting the results of these experiments disappear if it is assumed that the unknown radiation consisted of particles of mass 1 and charge 0, i.e. neutrons.

Chadwick's explanation was clearly satisfactory. It explained the results of his own experiments and also those of the Joliot-Curies and other scientists. For example, it explained the fact that the Joliot-Curies had been unable to deflect the new particles with a magnet; only charged particles are deflected by magnetic fields. In fact, after learning about Chadwick's work, F. Joliot said that had he and his wife known about Rutherford's suggestion that such a neutral particle existed they would probably have identified the neutron themselves.

Thus the picture of the helium atom shown in Fig. 23 explains the experimental observations. The discovery of the neutron also explained the existence of isotopes—different forms of an element which have the same chemical properties but have atoms of different masses. To explain about isotopes we will first have to explain the list of elements chemists call the Periodic Table.

Moseley and the Periodic Table

Chemists had found that when the elements were listed in the order of their atomic masses elements with similar chemical properties came at regular or periodic intervals in the list—hence Periodic Table. Fig. 24 shows a modern form of the Periodic Table. When the elements are arranged in this way the vertical columns each contain elements with similar properties. Thus the extreme right-hand column contains helium (He), neon (Ne), argon (A), krypton (Kr), xenon (Xe), and radon (Rn). All these elements are gases which have few, if any, reactions with other elements—they are the so-called inert gases.

1 H																	2 **He**
3 Li	4 Be											5 **B**	6 **C**	7 **N**	8 **O**	9 **F**	10 **Ne**
11 Na	12 Mg											13 **Al**	14 **Si**	15 **P**	16 **S**	17 **Cl**	18 **A** 39·944
19 K 39·096	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co 58·94	28 Ni 58·69	29 Cu	30 Zn	31 **Ga**	32 **Ge**	33 **As**	34 **Se**	35 **Br**	36 **Kr**
37 Rb	38 Sr	39 Y	40 Zr	41 Cb	42 Mo	43 (Tc)	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 **In**	50 **Sn**	51 **Sb**	52 **Te** 127·61	53 **I** 126·92	54 **Xe**
55 Cs	56 Ba	57–71 Lanthanides	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 **Tl**	82 **Pb**	83 **Bi**	84 **Po**	85 **At**	86 **Rn**
87 Fr	88 Ra	89– Actinides															

Fig. 24

Starting in the top left-hand corner and reading each row from left to right the Table shows the elements arranged in order of increasing atomic mass. The exceptions have their masses printed beneath them. The number at the top of each element is Moseley's atomic number.

The old version of the Periodic Table stuck strictly to the arrangement of the elements in the order of their atomic masses. This gave rise to several anomalies. For example, the atomic mass of potassium is 39·096 and of argon is 39·944, and so potassium came before argon. In Fig. 24, therefore, potassium occupied position 18 and argon occupied position 19. Thus potassium, a violently active metal, came in the middle of the group of inert gases. Although correct in order of atomic masses this arrangement was clearly wrong from the point of view of elements with similar chemical properties occurring in the vertical columns of the Table. A similar state of affairs held with cobalt and nickel, and also with tellurium and iodine.

As you can see these anomalies have been removed in the modern version of the Periodic Table printed in Fig. 24. This was the work of a brilliant young physicist named Moseley who worked in Rutherford's laboratory at Manchester. In 1913 Moseley examined how X-rays were diffracted by the atoms in a crystal. X-rays are produced whenever a fast-moving stream of electrons hit a substance. Moseley studied the X-rays produced when electrons hit different elements. The X-rays were diffracted by a crystal and then photographed. The photographs showed a definite series of lines for each element (Fig. 25).

The figure shows that there is a definite shift in the wavelength of the X-rays emitted as you go from one element to another. Moseley found that this was true for all the elements he examined. Fig 25 shows two of the X-ray diffraction lines for each element. The lines corresponding to the longer wavelength

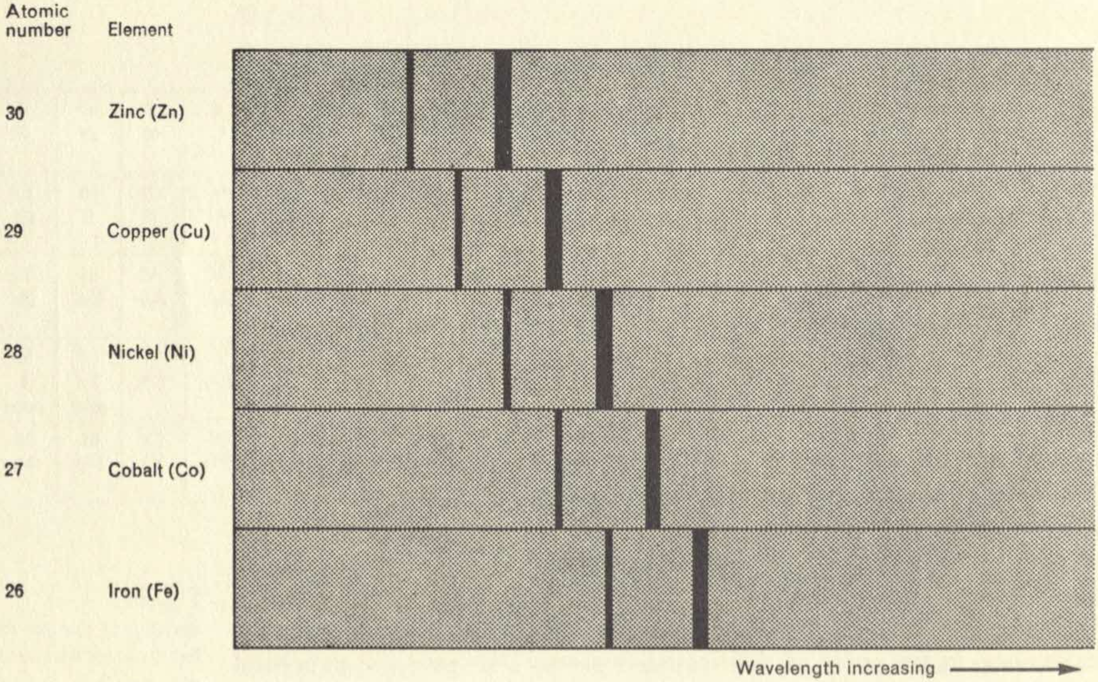


Fig. 25

X-ray diffraction picture showing two of the lines for the named elements.

of the two is called the K_α line and the other the K_β line. Moseley also found that if you take the square roots of the frequencies of the K_α lines for hydrogen, helium, lithium . . . and so on for all the elements up to uranium, the values increased regularly. Thus the value for helium was twice that for hydrogen; the value for lithium was three times that for hydrogen and so on. He gave each element a number proportional to this square root of the frequency: hydrogen 1, helium 2, lithium 3, . . . uranium 92. Moseley found that these atomic numbers gave the order in which the elements appeared in the Periodic Table but with an important improvement. The anomalies mentioned previously disappeared. The atomic number of argon is 18 and of potassium 19, and so in the new classification argon comes in its rightful place according to its chemical properties, i.e. before potassium and not after it as it did in the original classification. In addition to removing this and similar anomalies, Moseley found several gaps in his classification corresponding to atomic numbers 21, 61, 72, 75 for which elements had not yet been discovered. Since then these elements have been found. They are scandium (21), promethium (61), hafnium (72), and rhenium (75).

This fine work of Moseley's is all the more remarkable since he was only 26 at the time. His death two years later during the 1914–18 war was a great loss to science throughout the world.

Isotopes

After the war the scattering experiments of Geiger and Marsden were carried a step further by Chadwick and others. Calculations based on the results of these experiments showed that the number of positive charges in the nucleus of any atom is equal to the atomic number of that particular element. *The atomic number of an element is therefore equal to the number of protons in the nucleus of each atom in the element.*

It follows directly from this that the atomic number is also equal to the number of electrons in a neutral atom of the element, since to make it neutral an equal negative charge is required to balance the positive charge on the nucleus.

The number of protons in the nucleus of an atom clearly determines which element it belongs to and where it occurs in the new classification of elements. But the scattering experiments of Geiger and Marsden had shown that the number of protons in the nucleus only accounted for half the mass of the atom. From our discussion of helium earlier in this chapter it is clear that the nucleus contains neutrons as well as protons. The protons give the nucleus its positive charge and part of its mass, while the rest of its mass is made up of neutrons which, since they have no charge, do not affect the total charge of the nucleus as a whole.

The presence of neutrons in the nucleus also explained the existence of isotopes. Physicists studying radioactivity had found that the end products of the decay of uranium, actinium, and thorium were lead. These three specimens of lead were chemically identical; they reacted in exactly the same way when treated with acids and other chemicals. But they had atoms of different masses. In all there are seven varieties of lead which have identical chemical properties but different atomic masses. Since they behave alike chemically they all come in the same place in the Periodic Table. They were therefore called isotopes, from the Greek isos, meaning equal, and topos, meaning place. *Isotopes are different forms of the same element in which the atoms, although they have different masses, behave in the same way chemically.* To indicate which isotope is being referred to the mass is also given. Thus the lead which is formed from the decay of uranium is lead 206, since the mass of each of its atoms is 206. Uranium itself has isotopes, the one which decays to produce lead 206 is uranium 238. The other isotopes of uranium, U-235 and U-233, are important nuclear fuels which we will learn more about later.

From his work on positive rays (p. 14) J. J. Thomson had discovered that ions of different masses were deflected through different angles by an electric field. Light ions are deflected more than heavier ones (Fig. 26).

Thomson used his apparatus to deflect ions from ordinary non-radioactive elements and discovered that they too had isotopes. For example, the gas

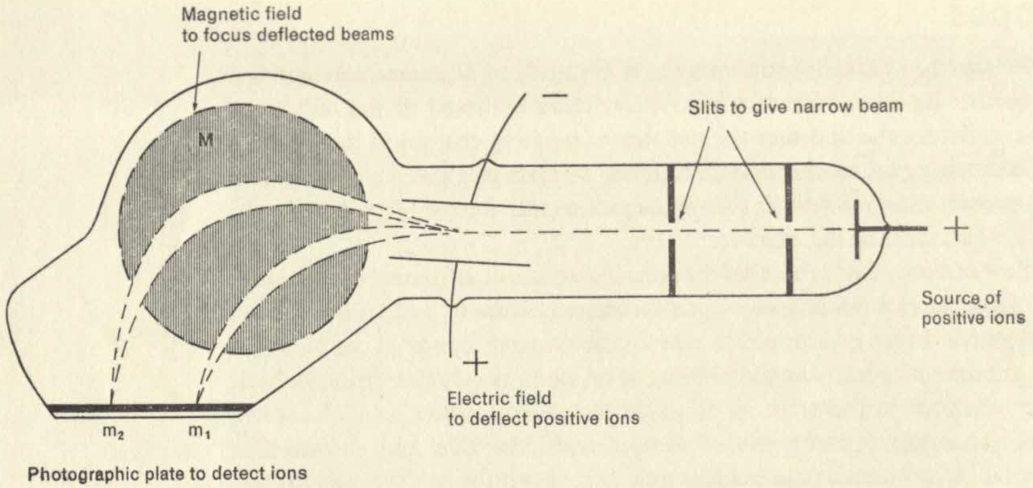


Fig. 26

Aston's improved version of Thomson's apparatus to measure the masses of different ions. The improvement was in the provision of the magnetic field which focused all the light ions at m_1 and all the heavier ions at m_2. From the dimensions of the apparatus and the strengths of the two fields the masses of the ions could be calculated.

chlorine, whose atomic mass is given by chemists as 35·5 actually consists of two isotopes, one with atoms of mass 35 and the other with atoms of mass 37. Any given amount of chlorine contains 75 per cent chlorine 35 and 25 per cent chlorine 37. This gives an average value for the atomic mass of 35·5 as found originally by the chemists.

This method of Thomson's was developed by Aston in 1919 and it is now one of the most accurate ways of finding the mass of the atoms in isotopes of different elements. On a large scale it can be used to separate isotopes in industry.

The existence of these isotopes is simply explained by the fact that atomic nuclei contain both protons and neutrons. Different isotopes of the same element must have the same number of protons but different numbers of neutrons. The fact that they have the same number of protons means they all have the same charge and are therefore forms of the same element, that they have different numbers of neutrons accounts for the different masses of the isotopes. Let us see how this works out in the case of the two isotopes of chlorine mentioned above. The atomic number of chlorine is 17, so each nucleus must contain 17 protons. The isotope chlorine 35 therefore contains $35 - 17 = 18$ neutrons, while chlorine 37 contains $37 - 17 = 20$ neutrons.

To find the mass of any particular atom or nucleus all we have to do is to add together the masses of its constituent parts. Thus the mass of a chlorine 37 nucleus should just be $20 + 17 = 37$. Accurate experiments however show that this is not the case. The mass of the nucleus always differs slightly from the mass of its constituent parts. This 'mass defect' represents the energy which binds the particles together and can be calculated using Einstein's discovery that mass and energy are equivalent (Chapter 6).

Defects of Rutherford's nuclear atom

We have now got a fairly good picture of an atom as a nucleus circled by electrons, and have seen further that the nucleus consists of neutrons and protons. But even this picture still has some defects.

An electron moving round the nucleus produces, due to its movement, an oscillating electric field. Imagine a point P just outside the orbit of the electron (Fig. 27). When the electron is close to P the electric field at P is strong. Suppose now that the electron moves in the direction of the arrow. As it gets further away from P the electric field at P gets smaller. When the electron is at its furthest point in the orbit, Q, the electric field at P will be at its minimum value. From then on the electron is getting closer and closer to P and so the electric field at P will increase until it reaches a maximum value again when the electron is nearest to P. For each revolution of the electron then, the electric field at P goes from maximum to minimum and then back to maximum value again. The electric field is said to oscillate. Whenever an electric field changes like this electromagnetic waves are emitted. This is basically the process by which radio waves are transmitted. These waves carry away energy from the electron. This means that the orbit of the electron should gradually get smaller and eventually the electron should be absorbed in the nucleus. But electrons in atoms do not lose their energy in this way. In 1913 the Danish theoretical physicist, Niels Bohr, solved this difficulty by assuming that the electrons in an atom had different energies. They could be thought of as revolving in different orbits round the central nucleus. Each orbit corresponds to a certain energy. When an electron is in one of these orbits no radiation energy is emitted. The fact that atoms do emit electromagnetic waves could be explained, said Bohr, by assuming that radiation is only emitted when an electron jumps from a high-energy orbit to a low-energy orbit; the surplus energy being emitted as electromagnetic waves. The difference in the energies of the orbits determines the type of wave emitted. This fitted in very well with the experimentally measured energies of such radiations. For instance electrons in the atoms of the sun jumping from high-energy orbits to low-energy orbits produce daylight.

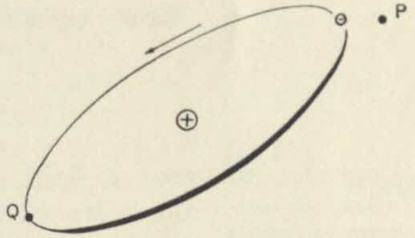


Fig. 27.

Another difficulty is the fact that the nucleus consists of positively charged protons together with neutrons. Why do the protons not repel each other and the nucleus fly apart? The electrical charges do repel each other, but there are much, much stronger forces which hold them together. These nuclear forces are still not completely understood.

Just as the picture of an atom as a tiny marble has been replaced by that of a nucleus circled by electrons, so even this idea has been superseded. Now the results of experiments are more completely explained by not having a picture at all, but by mathematical equations. This does not mean that our picture of the atom is no longer useful. It is. The advanced mathematics, quantum mechanics as it is called, is only used when more exact details are required. The simple picture of the nucleus with its orbital electrons is quite adequate for any explanations we shall need.

Chapter 6

Energy from atoms

Marie Curie and her husband Pierre found that radium was always at a temperature a few degrees higher than its surroundings. It keeps itself warm. All radioactive substances do this. This energy is different from any we have come across before; it comes from within the atoms themselves.

Energy and mass

But where exactly inside the atom does this energy come from? In 1905 Einstein, then only 26, put forward the startling theory that mass and energy are equivalent. Mass can be converted into energy, and energy into mass. He summed up this part of his theory in a simple equation:

$$E = mc^2$$

Energy = mass × the speed of light squared.

Now c, the speed of light, is very large—300 000 kilometres per second. When multiplied by itself to give c^2 we get 90 000 000 000—a very large number indeed. This means that a very small mass is equivalent to an enormous quantity of energy. If you could convert a lump of sugar (mass 2 grams) into energy in this way it would keep a single bar electric heater going continuously for 5 708 years.

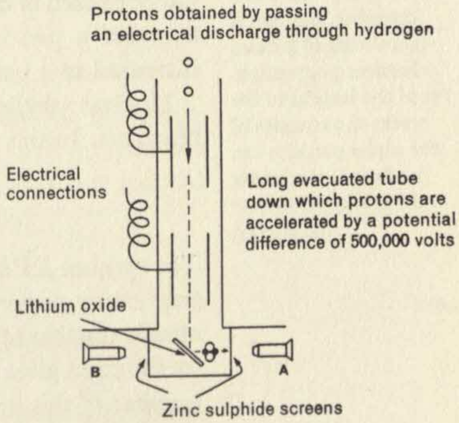

Protons obtained by passing an electrical discharge through hydrogen
Electrical connections
Long evacuated tube down which protons are accelerated by a potential difference of 500,000 volts
Lithium oxide
B
A
Zinc sulphide screens

Fig. 28

To show the principle of Cockcroft and Walton's experiment. When a flash on the zinc sulphide screen was observed at *A* one also appeared at *B*. That is, the particles produced by the impact of the protons are emitted in opposite directions. Exactly what should happen if the lithium 7 nucleus splits into two alpha particles.

Einstein's theory was so new and strange that many scientists did not think it could be true. Striking confirmation that it was true was provided by Bainbridge who used the results of an experiment performed by Cockcroft and Walton at Cambridge in 1932. First let us see what Cockcroft and Walton's experiment was about. They bombarded a layer of lithium oxide with fast moving protons, Fig. 28. This was done by using a very high voltage to accelerate protons down a long tube from which the air had been pumped. The beam of protons was directed so as to fall on a target covered by a layer of lithium oxide. When the voltage was about 125 000, particles were emitted from the lithium. These particles caused bright flashes on a zinc sulphide screen placed a short distance away. Even when the protons were accelerated by 500 000 volts there was only one flash for every 100 000 million protons. Walton, by using a cloud

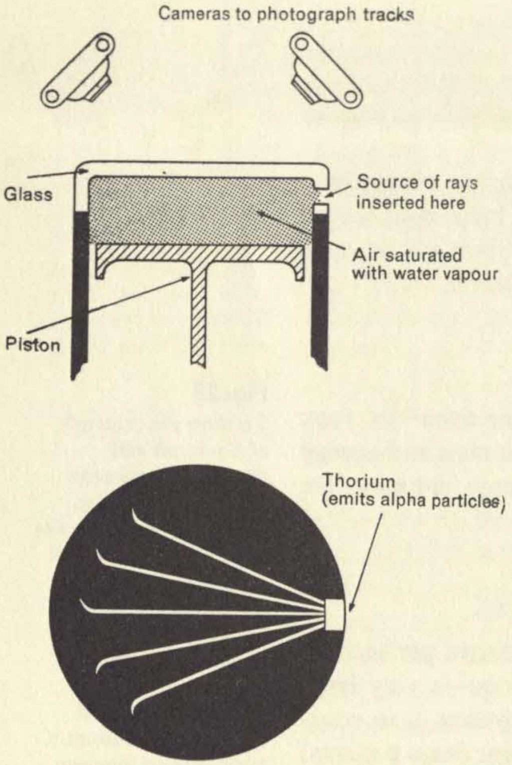

Cameras to photograph tracks
Glass
Source of rays inserted here
Air saturated with water vapour
Piston
Thorium (emits alpha particles)

Fig. 29

Principle of the cloud chamber. Beneath it is a sketch of a cloud chamber photograph. From the lengths of the tracks the energies of the alpha particles can be found: the longer the track, the greater the energy.

chamber, discovered that the flashes were produced by alpha particles.

A cloud chamber is an instrument which detects charged particles. The first cloud chamber was devised by C. T. R. Wilson in 1911. The principles on which it works are as follows. When a charged particle passes through a gas it knocks electrons out of the atoms of the gas and so the gas becomes ionized. A cloud chamber, Fig. 29, contains air saturated with water vapour. When the air is suddenly expanded it cools and tiny drops of water condense on any ions present. An alpha particle leaves a trail of ions and so water drops condense on them, leaving a clear track showing where the alpha particle has gone. Photographs of these tracks are taken and studied carefully.

In their experiment Cockcroft and Walton were the first men to split atoms by artificial means. By using alpha particles from a naturally occurring radioactive source, Rutherford had previously split nitrogen nuclei, converting them into an isotope of oxygen. What happened in Cockcroft and Walton's experiment was this: when an atom of lithium 7 was hit by a proton, the proton was absorbed, thus giving the nucleus a mass of 8 units. The nucleus then split, dividing into 2 alpha particles each of mass 4 units. The charges also balanced: the lithium nucleus contains 3 protons, so when a proton was absorbed the positive charges increased to 4 units, these were carried off, 2 on each alpha particle, Fig. 30.

Nuclear physicists have a simple kind of shorthand for writing these reactions. In this shorthand the above reaction looks like this:

$${}_3\mathrm{Li}^7 + {}_1\mathrm{H}^1 \longrightarrow {}_2\mathrm{He}^4 + {}_2\mathrm{He}^4$$

The symbol ${}_3\mathrm{Li}^7$ stands for the lithium nucleus. The figure to the left tells us how many protons there are in the nucleus. This as we have seen, is the atomic number of the element. The atomic number of lithium is 3. The figure on the right gives the total mass of the nucleus—the mass number. The mass number of this lithium nucleus is 7.

Mass number = number of protons + number of neutrons. The number of protons in the nucleus determines which element we are dealing with; the number of neutrons determines which isotope it is.

${}_1\mathrm{H}^1$ stands for the hydrogen nucleus which is just a single proton. ${}_2\mathrm{He}^4$

stands for the helium nucleus (1 alpha particle) which contains 2 protons and 2 neutrons.

In the same way $_{92}U^{235}$ stands for a uranium nucleus which has 92 protons and a total mass of 235 units. How many neutrons will it contain?

Number of neutrons = mass number − number of protons, from the above equation. Therefore the number of neutrons = 235 − 92 = 143.

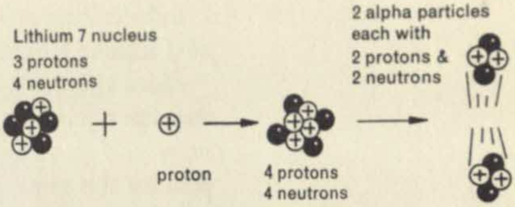


Fig. 30

Theoretical explanation of Cockcroft and Walton's experiment to split the lithium 7 nucleus.

A year after Cockcroft and Walton's experiment, in 1933, Bainbridge, working in the United States, and using the results of their experiment, found that in this reaction there is a loss of mass of 0·0185 units. From Einstein's equation $E = mc^2$ a mass of 0·0185 units is equivalent to an energy of 17·2 million electron volts. One electron volt is a convenient unit of energy to use in nuclear physics: it is the energy given to one electron when it is accelerated by a potential difference of one volt.

The energy of the emitted alpha particles in Cockcroft and Walton's experiment was calculated from the lengths of the tracks they produced in the cloud chamber. The longer the track the greater the energy of that particular alpha particle. The energy of the bombarding protons was known, and so the net increase in energy in this reaction (the energy of the emitted alphas minus the energy of the incident proton) was found. It was 16·95 million electron volts. This is only 0·25 less than the 17·2 predicted by Einstein's equation, well within experimental error and providing striking confirmation that his theory was correct. Since then many similar reactions have been studied. In all cases the equation $E = mc^2$ has been verified.

Binding energy

Einstein's equation enabled scientists to work out the amount of energy holding nuclei together. Take an alpha particle, for example. The mass of two separate protons plus two separate neutrons is greater than the actual mass of the resulting alpha particle. The actual figures are as follows:

Mass of 2 protons = 2 × 1·00758 = 2·01516
Mass of 2 neutrons = 2 × 1·00897 = 2·01794
Total mass = 4·03310

The actual mass of an alpha particle is 4·0028.

The loss of mass in the formation of an alpha particle from its constituent parts is therefore

$$\begin{array}{r} 4{\cdot}0331 \\ -4{\cdot}0028 \\ \hline \text{That is } 0{\cdot}0303 \end{array}$$

Substituting $m = 0{\cdot}0303$ in Einstein's equation $E = mc^2$ gives a value of 28·2 million electron volts for the energy.

Since there is a loss of mass in the formation of an alpha particle in this way the equivalent energy, 28·2 million electron volts will be released. Conversely, if we wanted to break up an alpha particle into separate neutrons and protons this same quantity of energy would have to be supplied. This energy can therefore be regarded as the energy which binds the particles together in the alpha particle and so is called the binding energy.

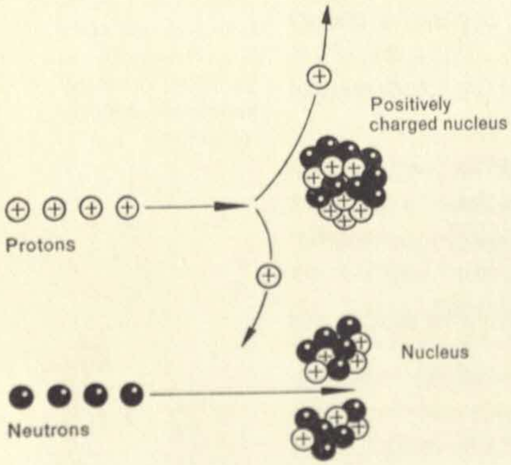
It is clearly impossible to get energy by attempting to split alpha particles. But it is possible to get energy from an experiment such as Cockcroft and Walton's which we have already described. The 17·2 million electron volts of energy liberated in their experiment, however, is only a tiny amount of energy. But if we could multiply this many times the release of energy would be large enough to use. A search for ways in which this could be done was immediately undertaken.

Splitting the nucleus

When a positively charged particle, like the protons in Cockcroft and Walton's experiment, approaches the nucleus of an atom there is a strong repulsion. This is because the nucleus also carries a positive charge and like charges repel each other. It is for this reason that only very few of the protons were able to hit the nuclei of the lithium atoms. The effect of the electrons can be ignored since the charge they carry is so small.

As soon as the neutron was discovered it was realized that here was the ideal bullet to fire at nuclei. The neutron, since it carries no charge, will not be repelled by the positive charge on the nucleus and will therefore be much more likely to hit its target. Fig. 31 illustrates this.

Fig. 31
Positively charged protons are repelled by the positive charged on the nucleus. Neutrons carrying no charge are not repelled and hit the nucleus.



In 1934 an Italian scientist, Fermi, and his colleagues investigated the effects of shooting neutrons at the nuclei of different elements. They discovered that slowly moving neutrons were more effective in splitting nuclei than fast ones. Fermi bombarded uranium with neutrons and found that the products, although not uranium, still emitted beta particles.

Later, in 1938, Hahn and Strassmann did a series of detailed experiments to find out what these beta-active substances were. With their helpers, Hahn and Strassmann found that the substances were barium and krypton. Barium has an atomic number of 56, rather more than half the atomic number, 92, of the original uranium. The atomic number of krypton is 36 (i.e. 92 − 56). The neutrons had not just chipped bits off the uranium nuclei, they had split them almost in half. This splitting of a heavy nucleus into two approximately equal halves is called fission. The two elements produced by the fission are known as fission fragments or fission products. Barium is therefore one of the fission products of uranium. Soon laboratores in all parts of the world reported the isolation of different fission products of uranium. There are in fact over thirty ways in which the fission of uranium can take place.

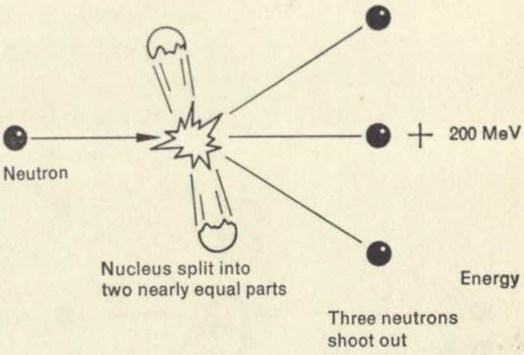


Fig. 32

Fission of U-235 nucleus. Sometimes more than 3 neutrons are produced, sometimes less. The average figure is about 2·5 neutrons per fission.

Chain reactions and critical size

Two startling facts emerged concerning the fission process. First, a large amount of energy was released. Up till that time the largest amount of energy liberated in nuclear reactions was 22·2 MeV (Million electron volts). In the fission process 200 MeV were liberated. This energy comes from a loss in mass and can be calculated using the equation $E = mc^2$. Second, in addition to the fission products, neutrons were shot out. There were sometimes two, sometimes three neutrons for each one which produced fission in the first place, Fig. 32.

If these new neutrons can be made to produce fission in other uranium nuclei more energy and neutrons will be liberated. In turn these new neutrons can produce further fission and so the reaction will spread. *A reaction which spreads from small beginnings in this way is called a chain reaction*, Fig. 33. Each fission produces some 200 MeV of energy so that once started a chain reaction will multiply this millions of times until a usable quantity of energy is produced.

However, to produce energy it is not just a matter of getting a piece of uranium and shooting neutrons at it. Natural uranium consists of the two isotopes U-238 and U-235. It is the U-235 isotope which is essential if a chain reaction is to be produced. Before any neutrons produced by fission can cause further fission, and so keep the chain reaction going, they must hit one of the U-235 nuclei. Unfortunately, in natural uranium there is only 1 atom of U-235 to every 140 atoms of U-238. When a neutron hits one of the U-238 nuclei more often than not it just bounces off or is absorbed and does not produce fission. Many neutrons bounce off nuclei in this way until they come to the surface of the uranium and escape to the surroundings. Clearly, if more

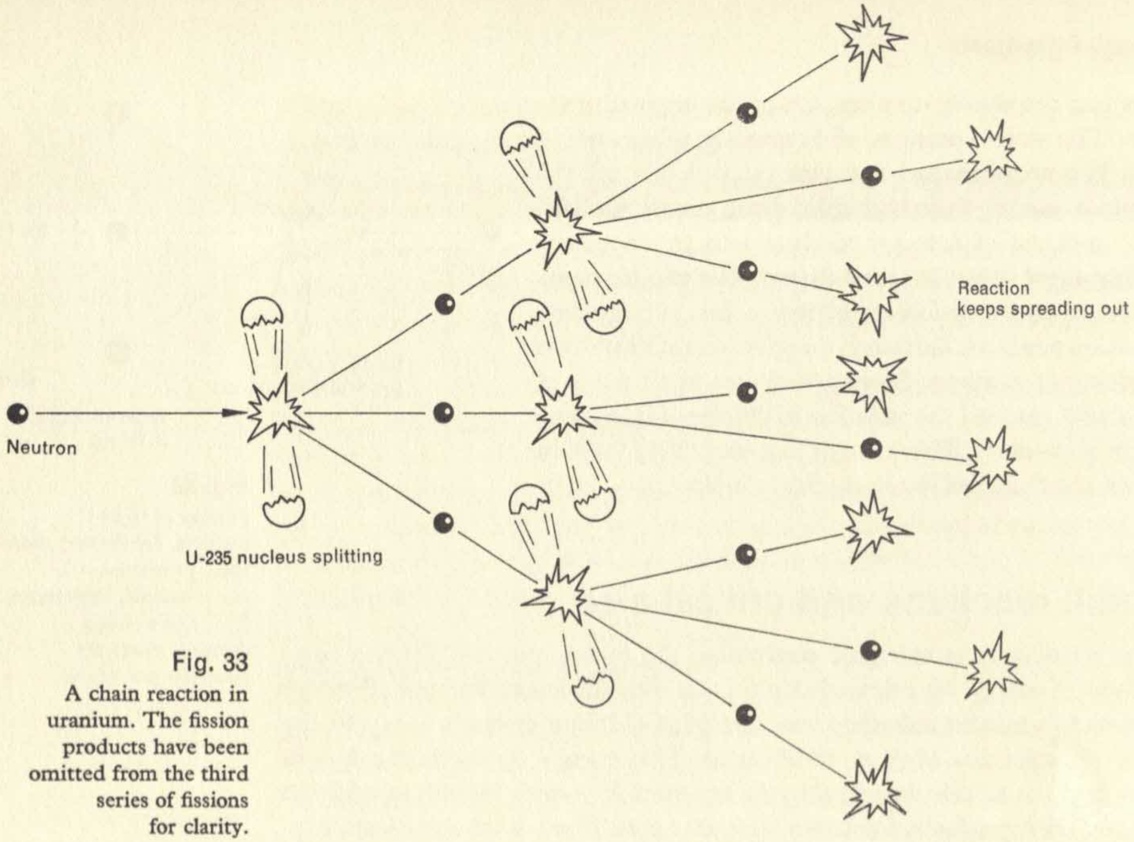


Fig. 33
A chain reaction in uranium. The fission products have been omitted from the third series of fissions for clarity.

neutrons are lost in these ways than are produced by fission, a chain reaction is impossible.

The number of neutrons absorbed can be reduced by getting rid of some of the U-238. The uranium then becomes richer in U-235. The other loss of neutrons by their escape from the surface can be reduced by using a bigger piece of uranium. The neutrons then have further to travel before they reach the surface, and the chance of their hitting a U-235 nucleus and causing fission before they get there is much greater than before. The size of the uranium is increased until the increase in the number of neutrons due to fission just equals the number lost either by leakage or absorption. An amount of uranium below this size will not sustain a chain reaction; an amount at or above this size will be able to maintain a chain reaction. When the number of neutrons produced by fission just balances those lost the uranium is said to be of critical size. Its actual value is still a military secret.

When two pieces of U-235 each just less than the critical size are brought together the combination will be bigger than the critical size. The chain reaction from neutron bombardment then proceeds so quickly that there is an explosion. This was how the first nuclear bomb was made. It was exploded at Alamogordo, New Mexico, on 16 July 1945. Although the terms atomic bomb and atomic energy are correct we have seen that the energy actually comes from the nucleus of the atom, therefore the terms nuclear bomb and nuclear energy are more accurate.

An uncontrolled chain reaction results in an explosion: the release of a vast amount of energy in an incredibly short time. In order to use this energy more profitably we must first learn how to control the chain reaction.

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Chapter 7

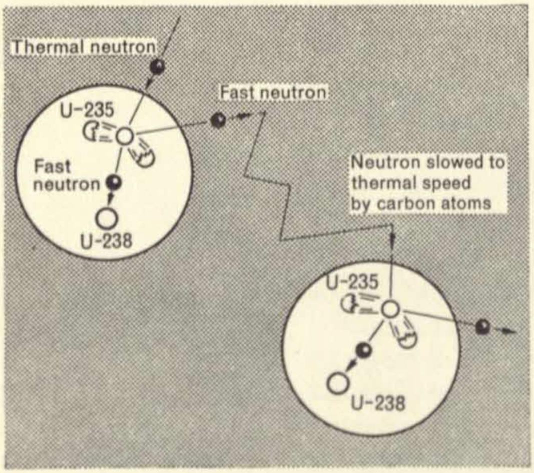
Controlling this energy

THE quantity of heat energy produced by nuclear fuels is fantastically large compared with that obtainable from oil or coal. For example, the quantity of heat produced by the splitting of all the nuclei in one ounce of U-235 is equal to that produced by burning about 60 tons of coal.

But as we have just seen, before we can produce any energy at all from the uranium we must have a certain quantity of it. If we have less than this critical amount, so many neutrons are absorbed or escape from the surface that a chain reaction of any kind is impossible. If a solid block of natural uranium is being used the critical amount is several feet high and wide, containing just less than 130 tons of uranium.

To keep the chain reaction going in natural uranium the energy of the neutrons must be reduced; otherwise they are scattered or absorbed by the U-238, and very few indeed produce fission. The neutrons are able to split the nuclei of U-235 most readily when they are travelling slowly: when, in fact, they have approximately the same energy as the molecules in the surrounding body. The neutrons are then said to be travelling at thermal speeds and are called 'thermal neutrons'. The energy of thermal neutrons depends on the temperature of the surrounding body, for example, it is only 0·025 of an electron volt at 20° C.

Fig. 34
To show the action of the moderator. The graphite which acts as moderator is shown by the light shading.



These thermal neutrons are produced by making the uranium into rods and surrounding these rods with graphite, a very pure form of carbon. The graphite slows down the neutrons without absorbing them. Any substance used for this purpose is called a moderator. Naturally, if there was too much graphite in between the rods of uranium the neutrons would be brought to a stop before meeting the next rod. In this case only a few nuclei in the one original rod would split, and then the reaction would stop. When the uranium fuel rods are separated by the right amount of the graphite moderator a chain reaction can take place. The action of the moderator can be clearly seen in Fig. 34.

In the left-hand rod of natural uranium, a slow moving thermal neutron has produced fission in a U-235 nucleus. In this case, one of the two fast neutrons shooting out has been absorbed by the U-238 nucleus in the same rod, and the other goes into the moderator. There, it travels in a straight line until it hits one of the carbon nuclei. Its direction changes sharply and it moves more slowly now because it has lost some of its energy in the collision. The neutron keeps hitting carbon nuclei and being slowed down, following the zig-zag path shown.

The spacing of the uranium rods is adjusted so that when it has slowed to thermal speeds the neutron enters the next rod. Here it produces fission with a U-235 nucleus and the process is repeated.

The core of each of the four reactors at Calder Hall in Cumberland contains over 1 000 tons of graphite.

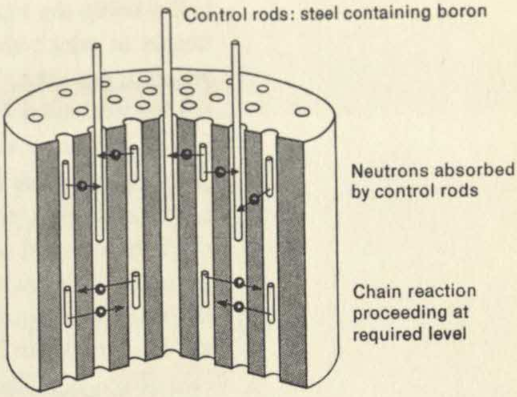

Control rods: steel containing boron
Neutrons absorbed by control rods
Chain reaction proceeding at required level

Fig. 35

Controlling the output of the reactor.

Once the chain reaction has started it can be controlled by limiting the number of the neutrons which produce fission. If we put into the pile of uranium rods and graphite some substance which absorbs neutrons the reaction slows down and the amount of energy released is reduced. If we remove this substance, the neutrons are no longer absorbed, and so more energy is produced because more U-235 nuclei are split. Such a pile of uranium rods and graphite is called a reactor.

Boron and cadmium are substances which absorb neutrons readily. The boron or cadmium is mixed with steel and made into control rods which can be raised or lowered into the reactor. When they are raised out of the reactor the reaction proceeds quickly, producing a great deal of energy. When they are lowered into the reactor neutrons are absorbed and the reaction, and hence the energy released, is reduced. It is arranged that if an accident occurs the rods automatically drop into the reactor, thus cutting off the reaction.

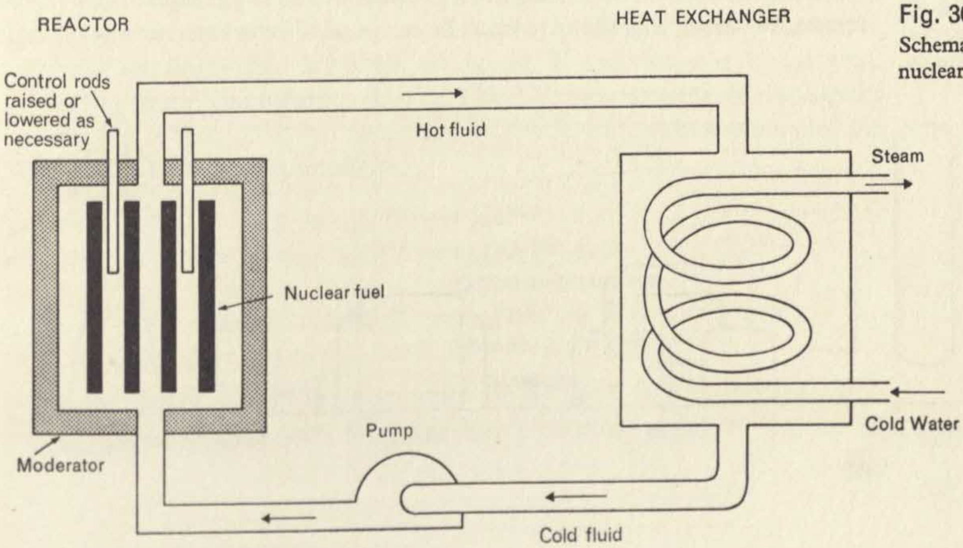


Fig. 36

Schematic diagram of a nuclear power reactor.

To bring the reactor into operation the control rods are slowly raised to a height at which they are capable of absorbing so few neutrons that a chain reaction can start.

One neutron at least is necessary to start such a reaction. There are always some neutrons present due to the action of cosmic rays from outer space, and the fact that some uranium nuclei split on their own and release neutrons. In addition to this, each reactor is given a special source of neutrons, both to start the reaction and to conduct other experiments.

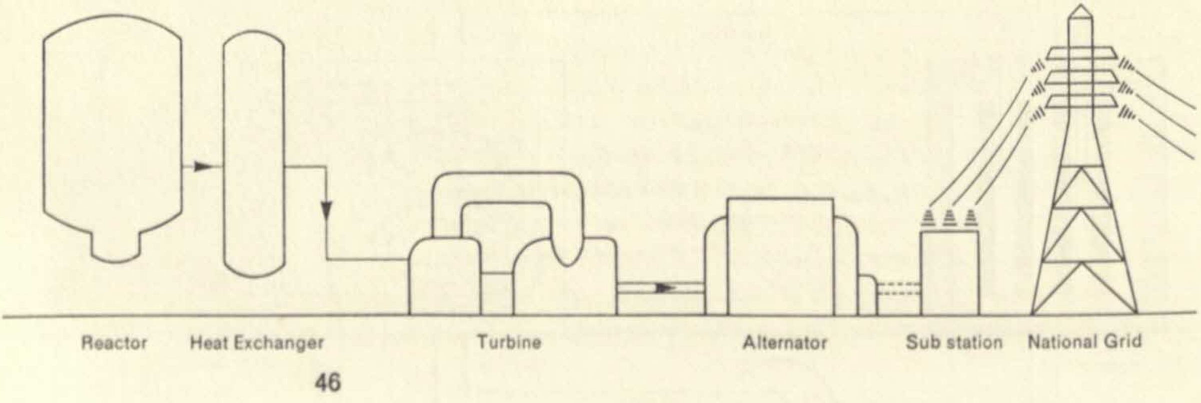
As the rods are raised further, the chain reaction goes more quickly, releasing more energy until the amount required is being produced. Then the rods are lowered again just far enough for the reaction to remain constant at this rate (Fig. 35). This can be done for any required power output up to the maximum value for any particular reactor, just as you can control the heat given out by some types of electric fire.

Having produced energy in this way we must now get it out of the core—the central part of the reactor—before we can make use of it. This is done quite simply as shown in Fig. 36.

A cooling fluid, either a liquid or a gas, is pumped through spaces between the uranium fuel and the moderator. The fuel has to be enclosed in a metal can to prevent chemical action between the uranium and the cooling fluid. As this coolant flows up in contact with the cans it absorbs the heat released by the fission of the uranium nuclei. The hot fluid now passes to the heat exchanger, where its heat passes from the fluid to cold water, turning the latter into steam at high pressure. This steam is then used to drive the turbines of an ordinary electric power station.

To remove the maximum amount of heat a lot of the cooling fluid must be pumped through as quickly as possible. The carbon dioxide gas which cools the reactors at Calder Hall is under a pressure of 100 lb per square inch. This means, of course, that the core must be surrounded by a vessel strong enough

Fig. 37
A nuclear power station.



to withstand this pressure. It is made of steel 2 inches thick. A ton of gas flows into this pressure vessel every second.

We might well ask, why not use the hot fluid to operate the turbines directly, so avoiding the extra expense and wastage of the heat exchangers? Here is the reason.

The heat exchanger is essential because, as the fluid passes through the reactor its atoms are bombarded by neutrons, so that some of them are made radioactive. Also, there is a possibility that the cans round the uranium fuel may leak, thus spreading radioactive waste products into the fluid. If the fluid went directly to the turbines, this radioactivity would spread, and might endanger workers in the power station.

This is also the reason why in any nuclear power station the reactor is always isolated from the rest of the machinery (Fig. 37).

Inevitably the reactor is emitting radioactive rays all the time. Therefore, to protect the men who operate it, the reactor is surrounded by a thick shield.

In the fast breeder experimental reactor at Dounreay in the North of Scotland the fuel used is plutonium. This has certain advantages over uranium as a nuclear fuel, one of the main ones is that with plutonium fast neutrons can be used to produce a chain reaction, and so a moderator is not needed. Consequently the core of the reactor is much smaller than the one at Calder Hall. Instead of being about the size of a house, it is nearer the size of a dustbin.

In this reactor, which started operation in November 1959, the core is surrounded by rods of U-238. The U-238 atoms are converted into plutonium. What happens is this, when a plutonium atom in the core is split it shoots out sometimes two, sometimes three neutrons. On average, for every two plutonium atoms split in the core five fast neutrons are produced. Thus, when four plutonium atoms in the core are split ten neutrons shoot out. Of these, four keep the chain reaction going by splitting other plutonium atoms, one is lost, and the remaining five are absorbed by the U-238. When a U-238 atom absorbs a neutron it changes to U-239. This U-239 is unstable and soon emits an electron to form an atom of neptunium. This in turn emits another electron to produce an atom of plutonium.

$$
\begin{aligned}
{}_0n^1 + {}_{92}U^{238} &\longrightarrow {}_{92}U^{239} \\
{}_{92}U^{239} &\longrightarrow \underset{\text{Neptunium}}{{}_{93}Np^{239}} + \underset{\text{electron}}{\beta^-} \\
{}_{93}Np^{239} &\longrightarrow \underset{\text{Plutonium}}{{}_{94}Pu^{239}} + \underset{\text{electron}}{\beta^-}
\end{aligned}
$$

So for each of the five neutrons absorbed by the U-238 an atom of plutonium is produced. In fact, for every four plutonium atoms we use up we produce five new ones. Because we have produced one extra atom of plutonium this process is called breeding.

Such a reactor is called a fast breeder reactor: 'fast' because fast neutrons cause the splitting, and 'breeder' because it breeds atoms of plutonium. At Dounreay it is used for experiments in finding new ways of using nuclear energy, and for testing materials used in the construction of reactors.

Plutonium is an example of an element which does not normally exist in nature—it has to be produced artificially in a reactor as described above. A number of such synthetic elements have been discovered, for example, technetium ($_{43}Tc^{99}$), promethium ($_{61}Pm^{147}$), astatine ($_{85}At^{211}$), francium ($_{87}Fr^{221}$)—these were elements which filled gaps in Moseley's Periodic Table as mentioned on p. 32. In addition to these, elements with atomic numbers greater than 92 (uranium) have been detected. These so-called trans-uranic elements have atomic numbers ranging from 93 to 101 and doubtless others have already been or are in the process of being discovered. All these synthetic elements are so unstable that if they did once occur in nature their atoms have long since disintegrated to form atoms of more stable elements.

But to get back to the fast breeder reactor at Dounreay. Heat is produced so quickly in the small core of this reactor that no gas can remove it fast enough. Instead, a mixture of the liquid metals sodium and potassium is used to carry the heat from the core into the heat exchangers.

This is a tricky process because both sodium and potassium react violently on contact with water, exploding and bursting into flame. There must, therefore, be no possibility of a leak in the cooling system. There is another danger because the liquid metal becomes highly radioactive—the reason why these particular metals are used and the solution of this problem belong to the next chapter.

We can see, therefore, that although the principles on which nuclear power stations work are quite simple, putting them into practice is far more difficult. In fact, it has required all the skill of our engineers to build nuclear power stations to the precision necessary if they are to work efficiently and safely.

Chapter 8

Making a nuclear reactor

As we have seen, the main parts of a reactor for power production are:

1. The fuel.
2. The moderator.
3. The control rods.
4. The coolant to transfer heat from the pile to the water in the heat exchangers.
5. The heat exchangers.
6. The safety shield to protect the operating staff.

The construction of each of these items presents difficult problems to the scientists and engineers who design and make reactors. The complexity of the problem can be seen from Fig. 38, which shows details of one of the reactor buildings at the Hinckley Point nuclear power station in Somerset. This is how some of these problems have been solved.

1 The fuel

There are two main fuels—uranium 235 and plutonium 239. Uranium 235 is present in natural uranium, but only in small quantities. Plutonium 239 can be made in a breeder reactor like the one at Dounreay.

If these fuels were just put into the reactor and the cooling fluid fed past them, a chemical reaction would take place and the channels containing them would soon be blocked. To avoid this, the pieces of fuel are enclosed in cans. So that the reactor will work efficiently, the metal from which the cans are made must have certain properties.

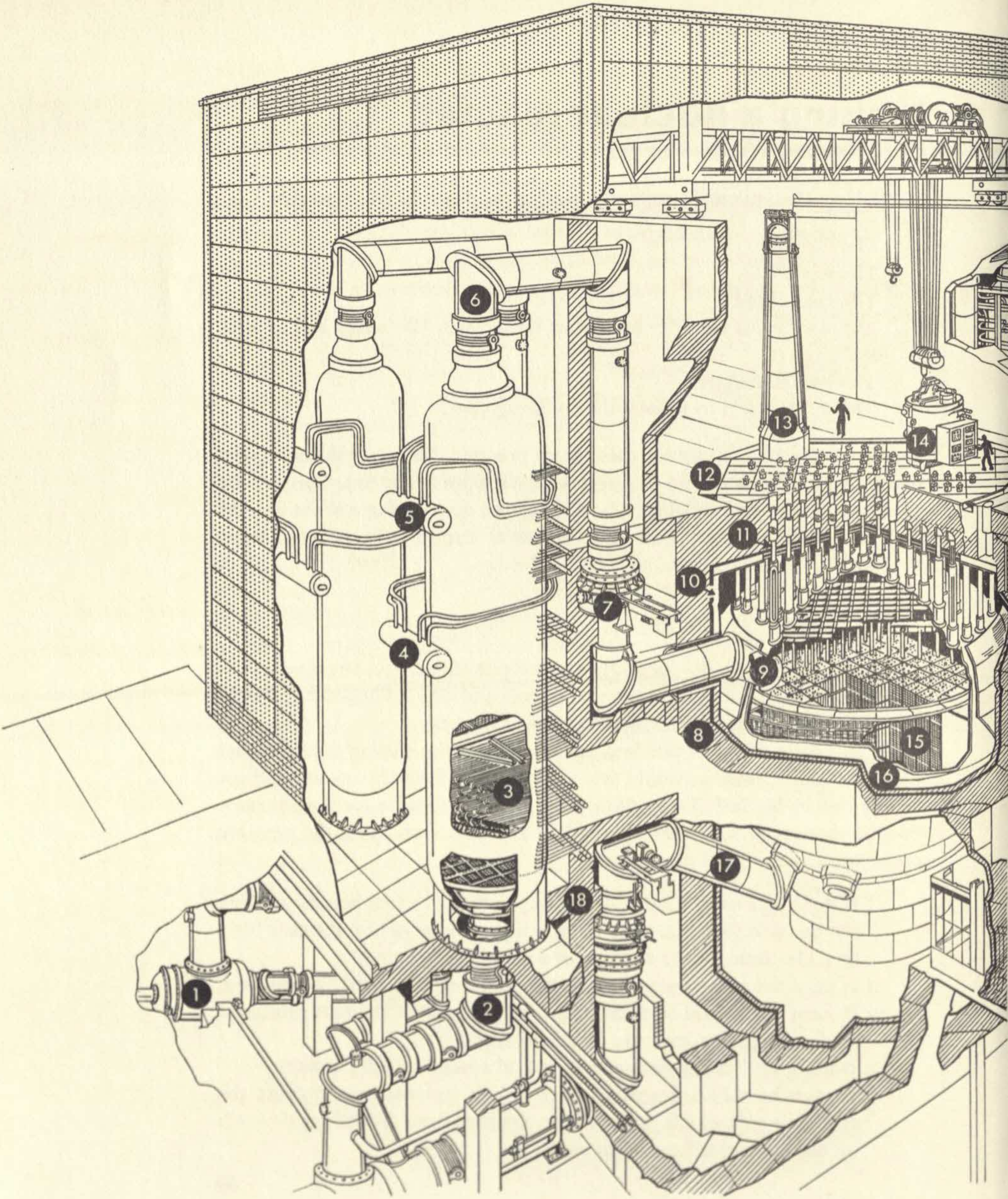
i It must be a good conductor of heat, so that as much heat as possible can be taken from the fuel. To help this transfer of heat the cans have fins, like those on the cylinder of a motor bike engine.

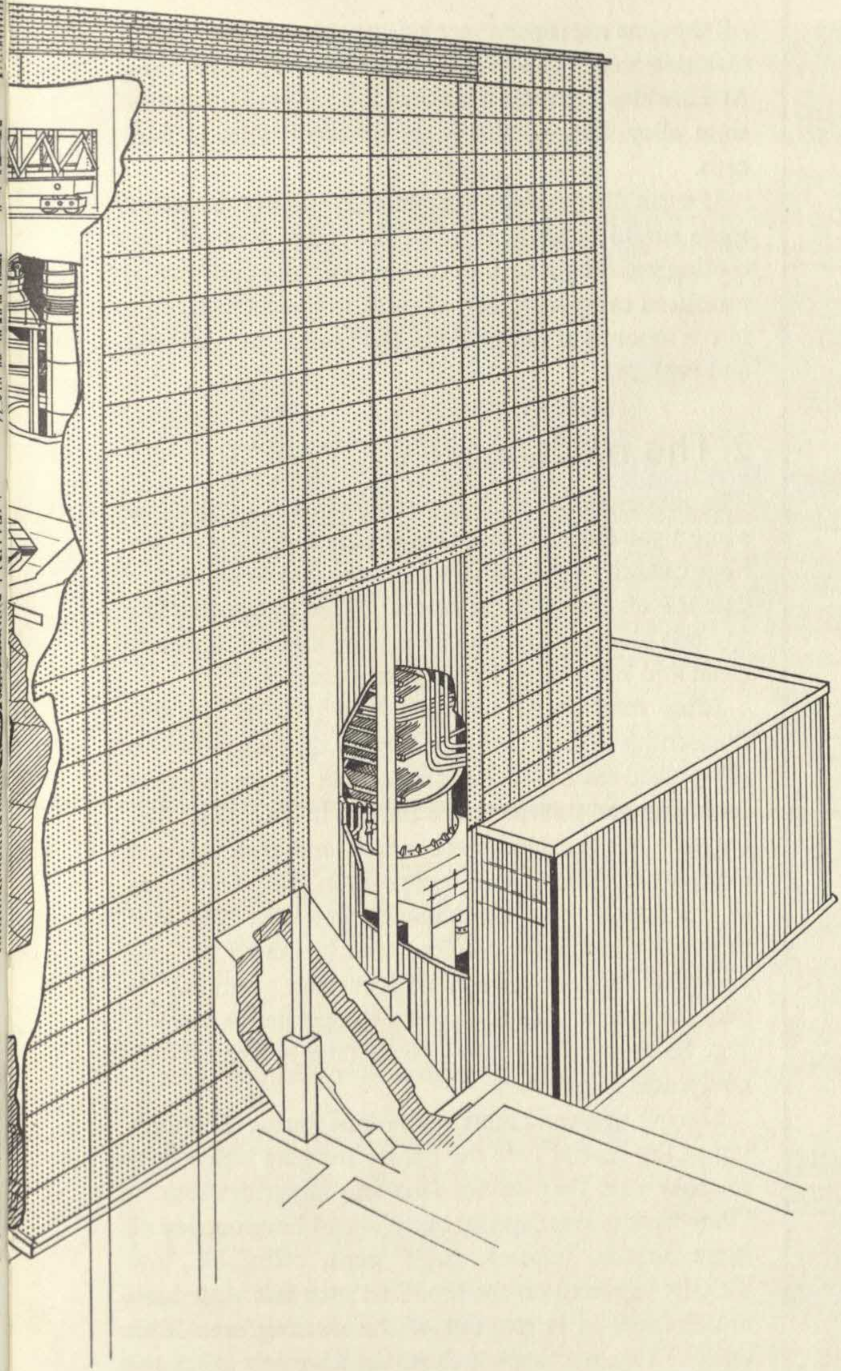
ii It must not absorb neutrons, or the chain reaction would be stopped.

iii It must not buckle or twist under the pressure of the new substance made at high temperatures inside the cans.

iv It must not leak, or radioactivity would spread into the coolant.

v It must be able to stand up to very high temperatures, because the efficiency with which power can be obtained from the reactor depends on the amount of heat taken out.





1 Coolant-gas circulating blowers.
2 Coolant gas outlet from steam raising unit.
3 Stud-tube elements.
4 Low-pressure steam drum.
5 High-pressure steam drum.
6 Coolant-gas inlet to steam raising unit.
7 Coolant-gas inlet gas isolating valves.
8 Main biological shield.
9 Coolant-gas outlet from reactor.
10 Thermal shield.
11 Charge tubes.
12 Charge floor.
13 Hole-preparation machine.
14 Charge and discharge machine.
15 Graphite-moderator core.
16 Reactor pressure-vessel.
17 Coolant-gas inlet to reactor.
18 Secondary biological shield.

Fig. 38
Sectional view of one of the two reactor buildings at Hinkley Point.

All the time experiments are being made to discover new materials which will fulfil all these exacting conditions. At Hinckley Point the fuel cans are made of a magnesium alloy. Fig. 39 shows six different types of fuel cans.

If a can did develop a leak when it was in the reactor there would be an increase in the radioactivity of the cooling gas. To detect this, the radioactivity of the gas is measured every half hour. If there is a sudden increase in the amount of radioactivity the faulty can is located and replaced.

2 The moderator

The moderator used at Hinckley Point is graphite—some 2 500 tons of it. Even the slightest impurity in this huge quantity would absorb neutrons and seriously impair the efficiency of the reactor. This means that the 132 000 blocks of graphite have to be kept scrupulously clean and must be laid with great accuracy.

After machining to correct size (accurate to one thousandth of an inch) at the factory they are individually packed and numbered, arranged in correct sequence for laying and transported to the site in covered lorries. On the site the blocks are stored and then vacuum cleaned before being placed in position. The positioning of the blocks is of particular importance. The fuel channels through the graphite must be exactly vertical, and other channels have to be accurately positioned to take the complicated equipment to operate the reactor. Fig. 40 shows the control room from which all this equipment is operated.

During these and other operations during the building of the reactor core the people working inside have to make sure they do not take any impurities into it. They have to wear special overalls and leave outside all loose articles, watches, rings, pens, coins, &c., not actually required on the job. The men and their tools are checked in to and out of the working area. This ensures that nothing which might adversely affect the working of the reactor is left behind.

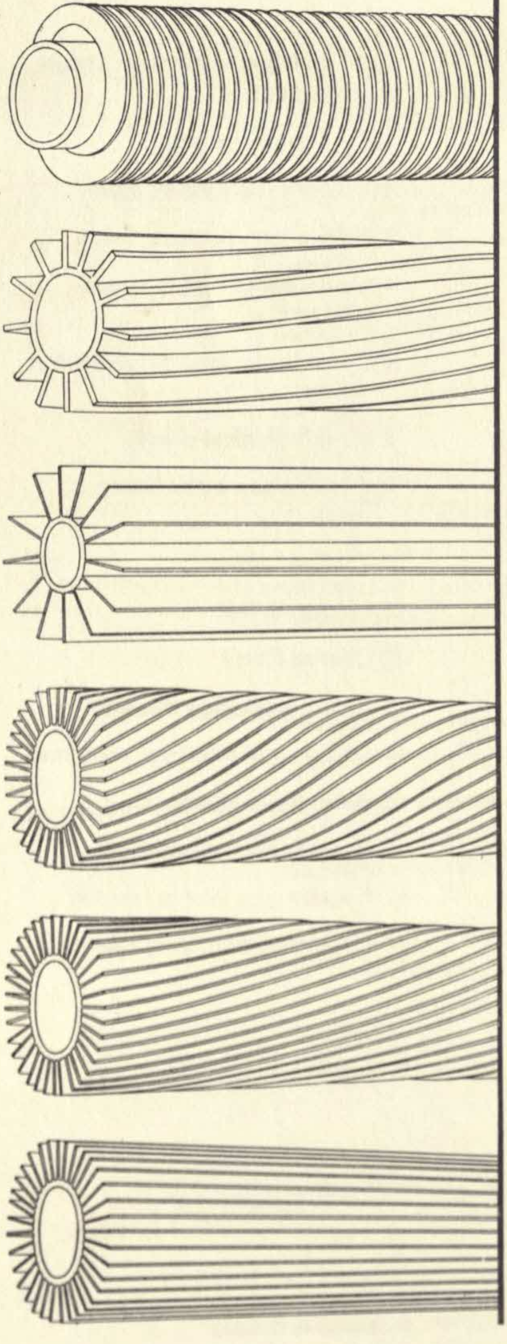


Fig. 39
Fuel cans.

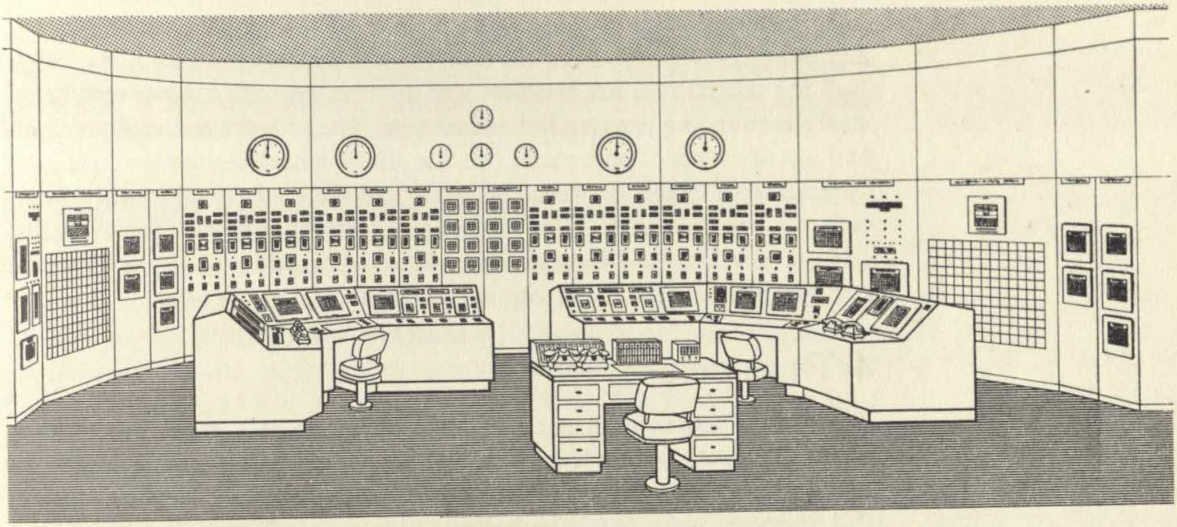


Fig. 40
The control room at Hinckley Point, showing the desks for the Station Control Engineer (centre) and the two Reactor Engineers.

Graphite is not the only possible moderator. Ordinary water and heavy water are two other substances which can be used. In heavy water the hydrogen atoms each have a neutron as well as a proton in the nucleus; this makes the molecule heavier than that of ordinary water, and hence the name. Graphite is by far the most commonly used moderator in reactors throughout the world. This is largely because pure graphite absorbs few neutrons and also because it is relatively cheap to produce. Beryllium, one of the other elements which could be used as a moderator, absorbs few neutrons but it is very expensive.

The hydrogen in ordinary water slows neutrons very well, but unfortunately it also absorbs them strongly. Heavy water is much better and only absorbs one neutron for every thousand that ordinary water absorbs. With heavy water you can have a much smaller reactor than one which is moderated with graphite, and so use less fuel with a consequent saving in initial fuel costs. However, heavy water itself is not cheap. It costs about £25 000 per ton and a large power reactor would require several hundred tons, plus yearly topping up.

Fast reactors like the one at Dounreay do not need to slow the neutrons down and therefore have no moderator.

3 The control rods

Next, a suitable material for the control rods has to be found. As the purpose of these rods is to absorb neutrons not required to maintain the chain reaction, a material which absorbs neutrons strongly must be chosen. Boron and cadmium are two such elements.

So that they can be easily fashioned into rods they are usually made of aluminium or steel which has the boron or cadmium mixed with it. At Calder Hall the control rods are stainless steel tubes lined with a 3 per cent boron steel sleeve and a 4 per cent boron steel core. The rods are mounted vertically and are raised out of or lowered into the pile by a flexible stainless steel cable operated by a motor. Between this motor and the drum to which the control rods are attached there is an electro-magnetic clutch. Any power failure releases this clutch, dropping the rods into the pile and so stopping the reaction immediately, before any serious damage can take place.

4 The coolant

The coolant performs the essential job of taking the heat energy produced by fission out of the pile so that it can be used. It must therefore conduct heat well and not absorb many neutrons. There are five main substances used for this purpose: gases (e.g. air, helium, nitrogen, carbon dioxide), ordinary water, heavy water, organic liquids, and liquid metals.

At present most power reactors mainly use carbon dioxide because it is convenient, cheap, and safe. It has some disadvantages since it is not as efficient as other gases in removing heat and at high temperatures it reacts with graphite.

Ordinary water is cheap and can be used as both moderator and coolant. In this case the water has to be under high pressure since otherwise it soon changes to steam. It is used in small reactors; the American submarine *Nautilus* has a pressurized water reactor.

Heavy water is similar to ordinary water as a coolant, but has the advantage that it does not absorb as many neutrons. Its disadvantage is its high cost. If its cost could be reduced there are tremendous possibilities for a reactor using heavy water as both moderator and coolant.

In the fast reactor at Dounreay the core is so small, and the quantity of heat produced is so great that a gas cannot remove it quickly enough. A liquid metal is the answer. The obvious choice would be mercury since it conducts heat so well, but unfortunately it absorbs neutrons strongly and so is not suitable. Liquid sodium absorbs few neutrons and conducts heat well, but it solidifies at 98°C so that when the reactor was cooled down all the pipes would become blocked. This difficulty is overcome by using an alloy of 22 per cent sodium with 78 per cent potassium which remains liquid at ordinary temperatures. Even so, this alloy is still difficult to deal with. In addition to reacting violently with water it also becomes highly radioactive. To prevent this radioactivity spreading a double cooling system has to be used. The first absorbs heat from the reactor core and becomes radioactive. The heat is then passed on to a second cooling system also filled with liquid potassium/sodium alloy. The radiation cannot penetrate the container of this second system which is consequently free from harmful radiation. The heat is then passed from the second cooling system to the water in the heat exchangers.

5 The heat exchangers

The heat exchangers themselves are a major undertaking. Each of the two reactors at Hinckley Point has six heat exchangers, each 90 ft high and 21 ft 6 in. in diameter, and weighing 300 tons. Partly manufactured at Renfrew in Scotland, they were transported to Somerset by sea. On the site they were completed and, after cleaning and testing, lifted into position by a specially constructed Goliath crane. This crane spanned the entire reactor building as shown in Fig. 41 and could lift 400 tons.

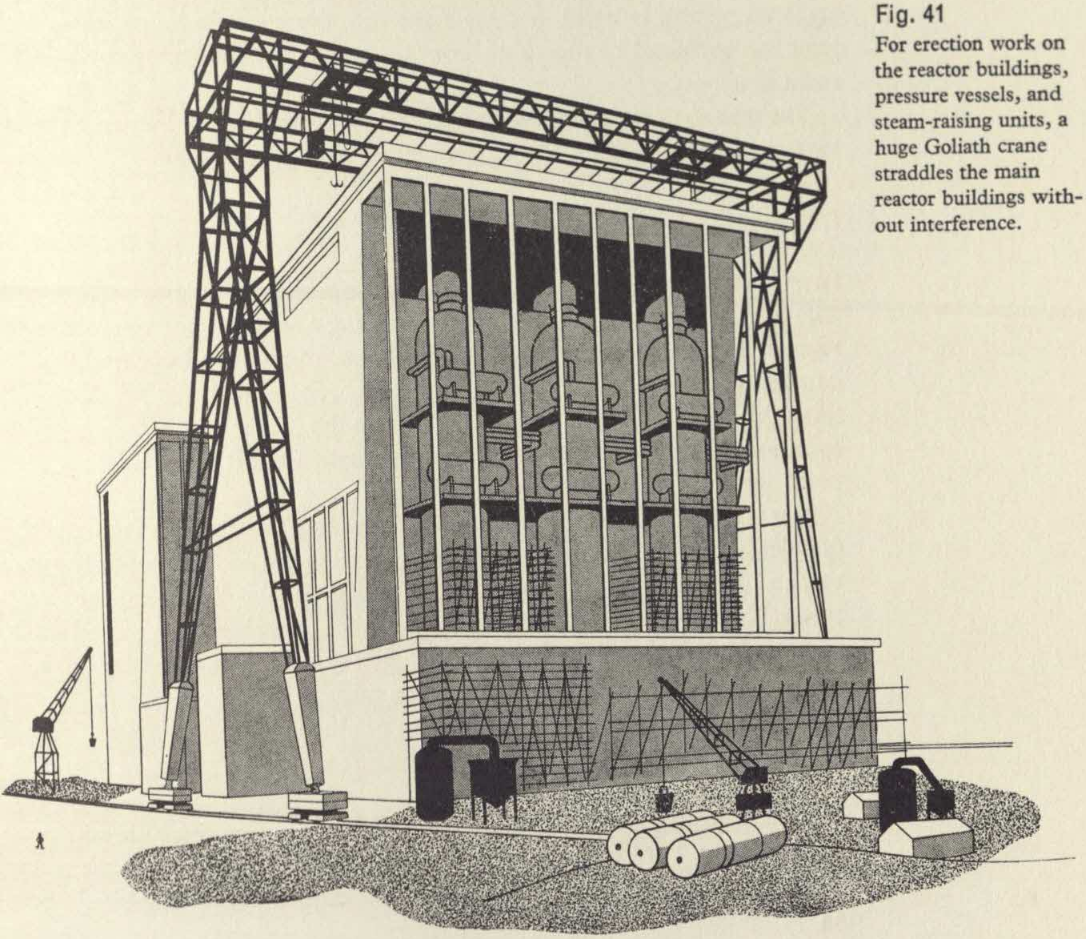


Fig. 41

For erection work on the reactor buildings, pressure vessels, and steam-raising units, a huge Goliath crane straddles the main reactor buildings without interference.

In gas cooled reactors the gas which takes the heat to the exchangers is fed through the core under pressure. The core is therefore enclosed in a large steel vessel which is strong enough to withstand the pressure of the gas inside it. The construction of such a pressure vessel also involves a large number of intricate welds. This welding sets up strains in the steel, and if nothing is done to remove these strains there is the possibility of fracture when the pressure inside is raised. The strains in the steel are removed by heating it carefully to about 650° C. At Hinckley Point this will be done by electric heating elements with an output of 3 500 kilowatts: equivalent to 3 500 single-bar electric heaters all switched on at once. This gigantic heater will be kept on for a week and then the steel vessel cooled slowly and evenly so that no new strains will be set up in it.

The container for the Dounreay fast reactor is the most complicated stainless steel vessel ever produced in Britain, and probably in the world. It took eighteen months to build, and, to make sure there would be no leaks, each joint was examined by means of X-ray or gamma ray photographs—3 750 of them in all.

The makers of the vessel set up a special school where welders were trained to use argon-arc welding sets to the highest possible standard.

6 The safety shield

In any reactor the chain reaction produces dangerous radiations, so the people who operate it have to be protected by building a shield round the core of the reactor. The main shield of the Hinckley Point reactors is a huge twelve-sided concrete casing 76 ft wide inside and 95 ft high, the walls being 7 ft thick. The lid of this enormous box is 11 ft thick. To stop the escape of the intense gamma radiation the concrete must be uniform throughout. If it is less dense at some point some of the harmful rays may escape.

Nor is it just a matter of building a solid wall of concrete. A large number of holes have to be made to take the tubes carrying the coolant, control apparatus, and fuel charging mechanism, all of which have to be placed very accurately. Naturally, radiation streams through these openings, so a second shield, rectangular this time, is built round the first one. This is 6 ft 6 in. thick.

The plans and specifications alone of a nuclear power reactor weigh some two and a half tons and cost £250 000 to produce, while a completed reactor can cost anything up to £55 000 000. Interest and repayments on a sum like this amount to some £15 000 per day.

Even when the reactor is completed and in operation there are still problems to solve. For example, the properties of all materials used in the reactor core are affected by the bombardment of neutrons. When graphite is bombarded by neutrons some of the atoms in the graphite move to positions between their normal ones. When the atoms are moved out of their normal positions in this way energy is stored in the graphite. E. P. Wigner was the scientist who first pointed this out, so this energy is known as Wigner energy.

In a reactor the Wigner energy stored in the graphite must be released from time to time or it would build up to danger level. The energy is released by letting the core heat up without the coolant flowing. When a certain temperature is reached the atoms begin to go back to their original positions—releasing the Wigner energy in the form of more heat. The release of the energy depends delicately on the temperature. If the initial heating is carried too far, this, together with the energy released by the atoms going back to their original positions, can raise the temperature in the core above danger level.

This is what happened in the accident at Windscale in 1957. A second heating was carried out in order to maintain the release of Wigner energy and this is believed to have caused unduly high temperatures in parts of the core. This caused one or more of the fuel cans to burst, the uranium inside began to burn, other cans burst and the graphite as well as the uranium began to burn, so the fire spread. The burning cans twisted and were jammed in the channels and therefore could not be removed. The fire was eventually put out by passing water through the cooling system.

In this accident a quantity of radioactive iodine escaped into the air. This radioactive iodine contaminated surrounding pasture land, was eaten by grazing cows and passed into their milk. No one was allowed to use milk from that part of the country until the radioactivity had disappeared. The reason for this requires a chapter of its own.

Chapter 9

The dangers of nuclear radiations

WHEN you have a bath your body absorbs heat energy from the hot water. Less than a hundredth of this amount of energy absorbed in the form of radiation would kill you.

Our bodies are affected by radiations from many sources: cosmic rays from outer space; the natural radioactivity of certain rocks which emit the alpha and beta particles, and the gamma rays we have already talked about; and inside our bodies we have small quantities of radioactive elements, potassium 40 and carbon 14. So far our bodies have been able to adapt themselves to this radiation, just as people who live near the equator are able to live comfortably in the intense heat.

But the amount of radiation the human body receives is increasing year by year. X-rays are used more and more for the detection of tuberculosis, the fitting of shoes and in the treatment of diseases such as cancer. Radioactive isotopes are being used extensively in medicine, industry, agriculture, and research, and this too increases the total amount of radiation that is already present.

Also, an important increase in the amount of radiation has come from the effects of nuclear explosions. Although nuclear bombs which release only small amounts of radiation—so-called 'clean' bombs—have been developed, tests with 'dirty' bombs which do release large quantities of radioactive materials still take place. When such an explosion takes place a huge mushroom-shaped cloud rises some 30 000 to 40 000 feet. This cloud contains 10 to 100 million tons of radioactive dust. The radioactive dust gradually falls out of the cloud, back to earth.

Fortunately most of the radioactive isotopes in this fall-out are short-lived: they soon lose their radioactivity and become harmless. This is also true of the iodine 131 released during the Windscale accident, so after six weeks it was quite safe to use milk from that area.

However, two isotopes in the fall-out from bombs have long half-lives: strontium 90 with a half-life of 28 years, and caesium 137 with a half-life of 33 years. The half-life is the time it takes for half the radioactive atoms present at any time to decay (see p. 24). For strontium, therefore, there will still be half the original number of radioactive atoms left after 28 years; 28 years later still there will be a quarter of the original radioactive atoms left, and so on. The particles of dust in the fall-out will thus be radioactive when they again reach the earth, and will continue to be radioactive for many years.

Strontium is the chemical which produces the red colour in fireworks. But the isotope strontium 90 was not known on earth before the testing of nuclear weapons. Nevertheless, strontium 90 is similar to calcium in that it is absorbed in the blood stream, and then deposited in the bones. The bones of the human body are hollow tubes. Inside, there is bone marrow which manufactures the red and white cells of the blood. When strontium 90 is deposited in the bones its radioactivity can affect the manufacture of blood and also cause bone cancer. Since the strontium 90 has a half-life of 28 years, and the body is continually taking in small amounts of it in food, the amount of strontium 90 in the bones must increase year by year, with subsequent increase in the risk of blood diseases and bone cancer.

Caesium 137, like strontium 90, was not present on earth before nuclear explosions. It spreads evenly throughout the whole of the body and its penetrating gamma radiation lasts for a long time—its half-life being 33 years. The body gets rid of about half the amount of caesium it has in it in six months, but during that time, since it is spread throughout the body, the gamma rays will have had a chance of affecting sensitive organs. This may produce damaging effects in the children of parents who have absorbed caesium 137.

Every living thing is made of cells. Different cells have different jobs to do: some make bones, others muscles, nerves and so on. They naturally differ in size, but are each of the order of a hundredth of a millimetre across.

The cells in the human body are continually splitting in two. In this way the body grows and replaces parts which have worn out or been damaged. This is a truly wonderful process, for when the exact amount of growth has taken place or damaged part of the body has been repaired, the cells automatically stop dividing. Sometimes however the process goes wrong and certain cells just keep on multiplying and never stop. This is the disease which is called cancer. Provided they are diagnosed soon enough, many forms of cancer can now be cured.

Every cell in the human body, and in all living things, contains an enormous number of tiny units called genes. All these genes together largely determine all the characteristics a person is born with. Each person gets his genes from his parents, who in turn got them from their parents and so on.

Genes can be changed by radiation, and the change passed on from parent to child. Experiments so far show that these changes are harmful, and can produce children who are mentally defective, or who are born with some physical disability. Unfortunately, there is no way of making damaged genes good; the defect goes on reproducing itself in each succeeding generation.

Moreover, radiation damage may not be obvious like measles or a cut finger. Cells within the body can be damaged without any detectable external effects. When these cells divide they carry the defect with them until months, perhaps years, later it has increased to such an extent that damage on a large scale has occurred.

Because of all this the designers and users of any equipment which produces radiation must make sure that the radiation reaching human beings is kept to a safe level. What a 'safe level' actually is cannot be stated with certainty, it is still a matter for research. Just as engineers make bridges stronger than the maximum load they have to bear, so scientists are confident that the radiations used for the peaceful applications of nuclear energy are below danger level. The point they are watching most anxiously, is that nuclear weapon tests and the future uses of radiation do not keep building up to the point when it will be unsafe to live on the earth.

Chapter 10

Handling 'hot' chemicals

You eat your dinner by remote control, and so do most people. Admittedly a knife and fork is not a very distant method of remote control, but they are a big help in dealing with hot food. Similar but more complicated methods have to be used when handling 'hot' chemicals.

Radio-isotopes are called 'hot' chemicals for two reasons. They are in fact at a higher temperature than the surroundings, and, just as you can burn yourself by getting too near to the fire so the particles and rays from radio-isotopes can 'burn' you. This means that they have to be handled carefully.

To avoid radiation danger to the operators, samples for irradiation are fed into reactors by pneumatic tubes or on a conveyor belt passing through a lead-lined alley. The active isotopes are taken out of the pile in the same way.

While one man operates long-handled tongs to remove the isotope another checks that the radiation does not exceed the danger level. He does this by using a detector called a radiation monitor.

Two of the many different kinds of radiation monitors used are the Geiger–Müller counter and the scintillation counter.

A Geiger–Müller counter, more often called simply a Geiger counter, is illustrated in Fig. 42. It consists of a straight wire down the axis of a metal cylinder. The wire and cylinder are insulated from each other and a voltage is applied between them. These electrodes are enclosed in a sealed glass tube which also contains an inert gas like argon.

When a charged particle or burst of gamma rays enters the tube the gas becomes ionized and a small pulse of current flows between the electrodes. These pulses are amplified and counted electronically. Thus each particle or burst of gamma rays which enters the tube is registered on the counter. The instrument is so sensitive that the counting rate may well be a hundred thousand counts per minute. Alternatively, the amplified current can be used to give an audible click in a loudspeaker. The more frequent the clicks, the stronger the source of radiation.

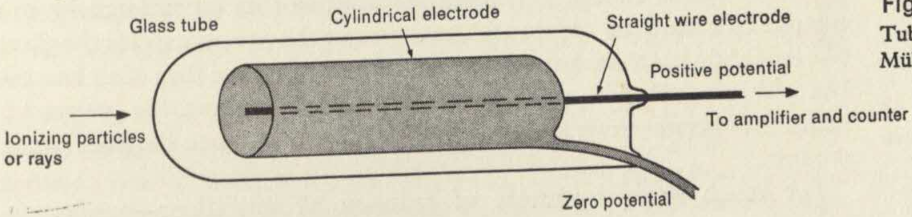


Fig. 42
Tube used in a Geiger–Müller counter.

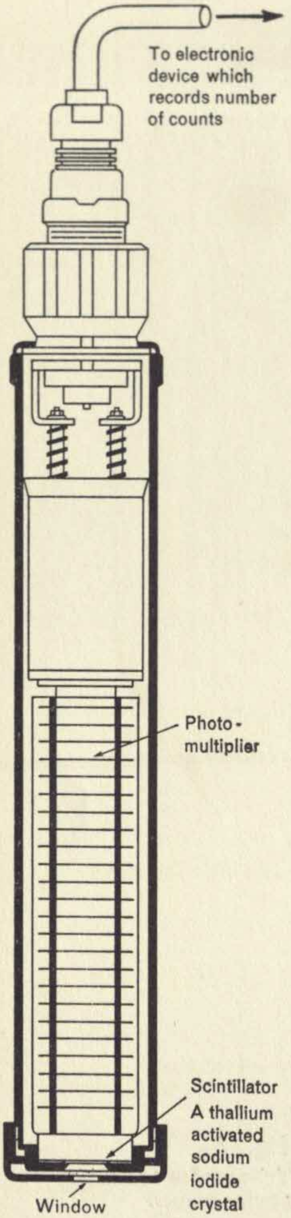

To electronic device which records number of counts
Photo-multiplier
Scintillator
A thallium activated sodium iodide crystal
Window

Fig. 43
A scintillation counter.

A scintillation counter really takes the place of the research worker counting the flashes on a zinc sulphide screen. Fig. 43 shows the arrangement of a typical scintillation counter. The rays enter the tube through the small windows at the bottom. These are kept narrow so that only radiation from the required direction will be taken into account. Different designs of scintillation counters are used for detecting beta particles, alpha particles, and gamma rays. They can also be used to detect neutrons. For example, using a scintillation counter it is possible not only to count bursts of gamma rays but also to measure their energies.

The crystal of sodium iodide in the counter is made sensitive by the presence of a small amount of thallium. In this crystal each burst of gamma rays produces a tiny flash of light. This tiny flash is then converted to a pulse of electricity and multiplied many times in the photomultiplier tube. This much greater pulse of electricity then operates an electronic counter. Gamma rays of greater energy produce brighter flashes of light and hence bigger pulses of electricity in the photomultiplier tube. By having the necessary circuits in the counter these higher energy gamma rays can be sorted out from the rays of lower energy.

Instruments such as these are often combined in special monitor units such as the hands and clothing monitor shown in Fig. 44. The hands are placed through the flaps near the top of the monitor. Two detectors inside are then switched on automatically and count for a pre-set time, usually a few seconds. The counts for each hand are displayed on the meters at the top of the monitor. If the count is above that permitted (600 counts per minute per hand for alpha particles and 6 000 counts per minute per hand for beta particles) a red warning light comes on or a buzzer sounds an audible warning. The two probes which can be seen hooked up beneath the hand flaps are for checking clothing. The one on the left is for beta particles and gamma rays, and the probe on the right detects alpha particles.

Every place where radioactive isotopes are used has instruments such as these to detect possible radiation leakage. The amount of leakage is usually very small. This is because such good precautions are taken when handling radioactive materials. For dealing with isotopes which are alpha or weakly beta active, glove boxes are used. A glove box is a totally enclosed small chemistry bench, Plate I. It is totally enclosed so that no radioactivity can escape. To make quite certain that none escapes the pressure inside the glove box is slightly less than the pressure outside; any leaks are then of air into the box and not radioactive particles out into the atmosphere. To protect his hands the operator wears plastic gloves which are sealed into the front face of the box.

For much stronger sources of radiation all operations—purification, machining to correct size, and so on—must be done behind thick lead or concrete walls. When only the simplest operations have to be performed, for example transferring a radioactive sample from one container to another, long tongs which are sealed into the wall are used, Fig. 45. More complicated operations are possible with another piece of remote handling equipment called a Master Slave Manipulator. Plate II shows a Master Slave Manipulator in operation. Shaped hand-pieces take the thumb and first two fingers of the operator's hands. Each hand-piece is connected by a boom which goes through the concrete wall into the 'hot' cell, and is connected to a set of metal jaws. Any movements of the operator's hands are then reproduced by these jaws. This enables him to carry out all the normal functions of routine chemical work: the picking up of test tubes, pouring of exact amounts of liquids from one vessel into another, weighing objects on a chemical balance and so on. Each 'hand' contains over five hundred moving parts. To reduce friction to a minimum and make them as efficient as possible, the Master Slave Manipulators are made of light alloys and stainless steel and are very carefully counterbalanced. The jaws can be used to manipulate weights of up to 5 lb without too great a strain on the hand and wrist of the operator. In an emergency weights of up to 22 lb can be lifted by one hand, but only if they are suspended by a wire instead of being gripped in the jaws.

In order to see what he is doing the operator looks through a window let into the protective concrete wall. To afford the same protection as the concrete, the glass is made with a high content of lead and is 3 feet thick. Sometimes the windows are made with glass on each face, but with the intervening space filled with zinc bromide solution. To give the same protection as the concrete wall this type of window has to be 4 ft 6 in. thick.

In some cases the operator must have a close-up view of objects in the 'hot' cell. This is done by using a small television camera. With two such cameras a three-dimensional view can be obtained if required. Plate III

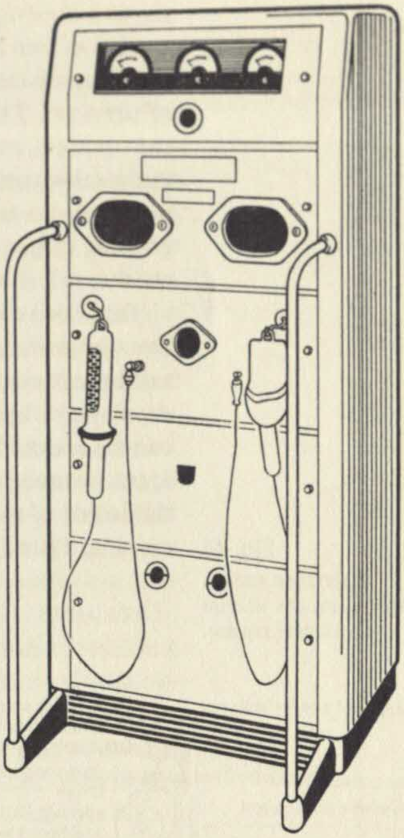


Fig. 44

Hands and clothing monitor used in nuclear power installations.

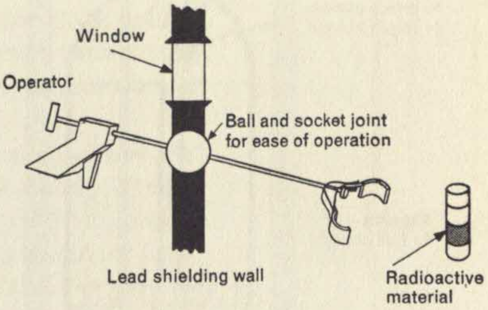


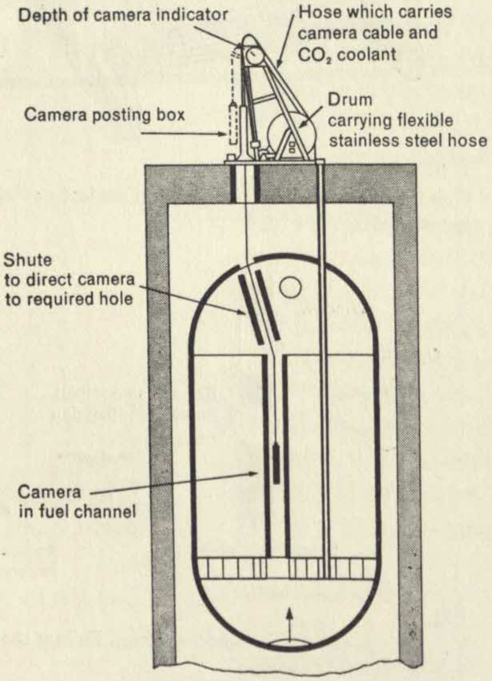
Fig. 45

Simple form of remote handling tongs. Pulling the 'trigger' closes the tongs.

shows a close-up camera in use in a 'hot' cell at Dounreay. In this cell tests are carried out on fuel elements which have been used in the fast reactor. Here the close-up camera enables the engineers to look at the exterior of a sample of uranium. This apparently simple operation is complicated by the fact that the uranium, owing to its radioactivity, is developing heat. This is true for all radioactive materials in the cell and to keep them cool they are kept under water whenever possible. When this cannot be done the material is cooled by blowing carbon dioxide on it. The other two engineers in the picture are using another television camera to observe what is going on inside the cell.

Television also plays an important part in the operation of nuclear reactors. Once in operation the core of the reactor becomes highly radioactive and cannot be examined by ordinary methods. Now, a television camera has been developed which can examine the interior of the channels in the core. The camera is cylindrical in shape, 48 inches long and only 3·5 inches in diameter. It can be used even when the outside temperature is as high as 200° C, although the inside of the camera is kept at 50–60° C by a cooling draught of carbon dioxide. Plate IV shows the interior of the camera. Built-in lighting is provided by four 25-watt lamps grouped round the lens. This is sufficient for observing objects up to 3 feet away when the camera is being used in a black graphite fuel channel.

Fig. 46
Television camera inspecting the interior of a nuclear reactor.


Depth of camera indicator
Hose which carries camera cable and CO_2 coolant
Drum carrying flexible stainless steel hose
Camera posting box
Shute to direct camera to required hole
Camera in fuel channel

The sides of the channel have to be viewed by a sideways viewing mirror since the lens itself points vertically downwards. An electric motor controls the movement of the mirror so that the operator can look at objects all round the camera. The operator can also pick up small objects in front of the camera by using a manipulator attachment which is fitted with tongs.

Fig. 46 shows the camera in use. The posting box with the television camera inside it is hoisted from the trolley, lowered over a valve on the top of the reactor and firmly bolted in position. After making sure that no radioactive gas can escape, the valve is opened to give access to the interior of the reactor. The camera is then lowered into position on a chute which can direct it into the channel to be inspected.

Methods of observation and handling such as those described above mean that radioactive materials can be handled safely and with a high degree of precision. These methods have made plants where radioactive materials are used some of the safest industrial places in which to work.

Chapter 11

Getting the uranium

URANIUM is refined at the Springfields works of the Atomic Energy Authority near Preston, Lancashire. Before you can actually go and see the uranium being refined in this plant there is a security check and you also have to wear special clothing. Special clothing is necessary because otherwise you might pick up radioactive dust and carry it away with you. The dust emits alpha particles, and although they cannot penetrate the skin they could be dangerous if some of the dust was accidentally swallowed. The plant is so well organized that mouth protections are not usually necessary. Only when radioactive compounds are actually moved by hand do the workers have to wear special masks.

In the changing room a low bench separates the normal side from the plant side. After putting on a long white coat and white hat the visitor takes off his shoes and puts them in a rack, together with any matches or sweets he might have. These are left behind so that he will not be tempted to eat or smoke while on the plant; if he did he might swallow some of the dust. Then, sitting on the bench he swings his legs over on to the plant side and, without touching the floor, puts his feet straight into white rubber boots, like sawn-off wellingtons.

The plant is laid out in two straight lines. Ore from the minefields comes in at one end and finished fuel rods in cans go out of the other end. Let us see just what happens at each stage.

The ore, concentrated at minefields such as Radium Hill and Rum Jungle in Australia contains up to 70 per cent uranium oxide. It arrives at Springfields in large drums. The drums are then opened in a totally enclosed container fitted with extractor fans. The fans take away any dust which otherwise would escape into the air and be swallowed by the workers. Next, a sample of ore from each drum is taken to be analysed. This is important because the price of the ore depends on how much uranium it contains, and uranium is very expensive.

From here the ore goes to be tipped into hoppers, again totally enclosed and fitted with extractor fans. A screw feeder in the hopper turns slowly, feeding the yellow ore into large stainless steel dissolvers. Here the ore is mixed with nitric acid which dissolves the uranium and any other metals present to form uranyl nitrate and other metallic nitrates.

The nitric acid does not dissolve everything, so the solid impurities left have to be filtered off. This is done by using a large rotary vacuum filter as shown in Fig. 47. The filtering material is a fine powder which is built up layer by layer on the outside surface of the drum until it is some 2·5 inches thick. Tubes go from the inside of this surface to a pump which produces a vacuum. Thus, when the filter is in contact with the solution in the trough, the difference in pressure produced by the vacuum forces the solution through it. The uranyl and other dissolved nitrates go on to the next stage in the process, and the solid impurities are left behind in the filter. These impurities may still contain traces of uranyl nitrate, so they are removed by a knife edge as the drum rotates, washed and fed back to be filtered again. This makes sure none of the valuable uranium compound is allowed to escape.

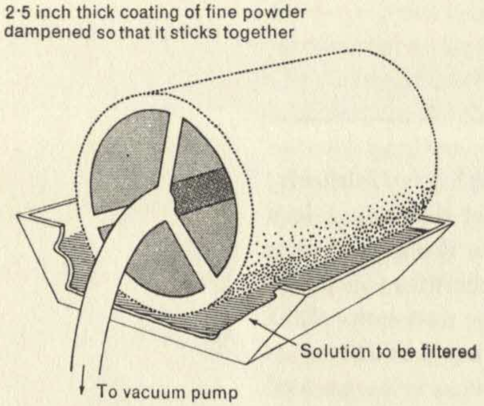

2·5 inch thick coating of fine powder dampened so that it sticks together
Solution to be filtered
To vacuum pump

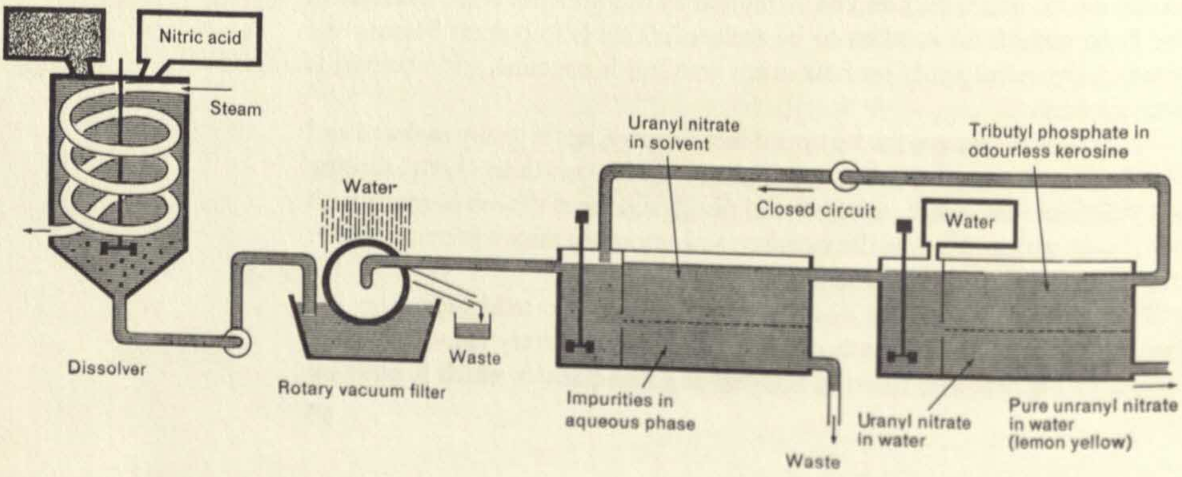
Fig. 47

To illustrate the action of the rotary filters.

The filtered liquid uranyl nitrate still contains some dissolved impurities (the other metallic nitrates) which have to be removed. This is done by a process known as solvent extraction.

Uranyl nitrate dissolves more readily in certain solvents than in others. A mixture of solvents which is particularly good at dissolving it is tributyl phosphate (TBP for short) and odourless kerosine. This mixture is stirred up with the impure uranyl nitrate and some more nitric acid added. The TBP and odourless kerosine 'soak up' just the uranyl nitrate, leaving behind the impurities which are held in the nitric acid. The mixture of TBP, odourless kerosine, and uranyl nitrate is less dense than the impurities and nitric acid. So after all the ingredients have been mixed thoroughly they are allowed to settle; since it is less dense, the mixture with the uranium compound in it floats to the top and can be run off. After this it is stirred up with pure water. The uranium compound passes into the water, leaving the pure TBP and kerosine to settle out on top while the pure uranyl nitrate in water is run off at the bottom (Fig. 48).

Fig. 48


Nitric acid
Steam
Dissolver
Water
Rotary vacuum filter
Waste
Uranyl nitrate in solvent
Closed circuit
Tributyl phosphate in odourless kerosine
Water
Impurities in aqueous phase
Waste
Uranyl nitrate in water
Pure unranyl nitrate in water (lemon yellow)

As kerosine is highly inflammable there is always the risk of fire. To reduce this risk the solvent extraction plant is on the roof, open to the air so that the dangerous vapours can be blown away.

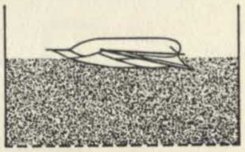
We now have to extract the uranium from the pure uranyl nitrate. It is first converted into uranium tetrafluoride, a process which is accomplished in three separate stages.

In the first stage water and nitrous oxides are removed from the uranyl nitrate to leave uranium trioxide. The uranium trioxide is in the form of a powder. A powder is difficult to move about, but liquids are much easier to deal with. A powder can be made to act like a liquid—it can be fluidized—by passing a current of gas up through it. Fig. 49 shows an experiment with sand and air to illustrate this fluidizing principle. Air is therefore blown up through the uranium trioxide and it is then easily transferred to the next stage.

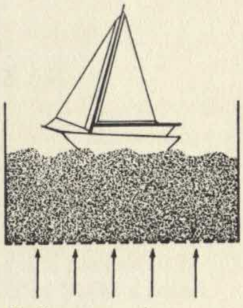
Here hydrogen is the gas which fluidizes the powder. Since the hydrogen is actually blown upwards through the powder it makes very good contact with it. This means that the chemical reaction which takes place when it is heated is much more efficient than if the gas was blown over the surface of the uranium trioxide. Each molecule of uranium trioxide contains three atoms of oxygen. When the reaction has finished, the hydrogen has taken one atom of oxygen from each molecule to leave behind uranium dioxide: the hydrogen has reduced the uranium trioxide to uranium dioxide.

In the third stage this uranium dioxide is converted into uranium tetrafluoride, this time by the upward passage of the gas hydrogen fluoride. It is quite obvious when these reactions have been completed because the uranium tetrafluoride is green in colour, as compared with the lemon yellow of the original uranyl nitrate (Fig. 50).

Very fine mesh holds sand in but allows passage of air



No air blown upwards, ship lies on surface of sand



Air blown upwards fluidises sand and ship floats just as it would on water

Fig. 49

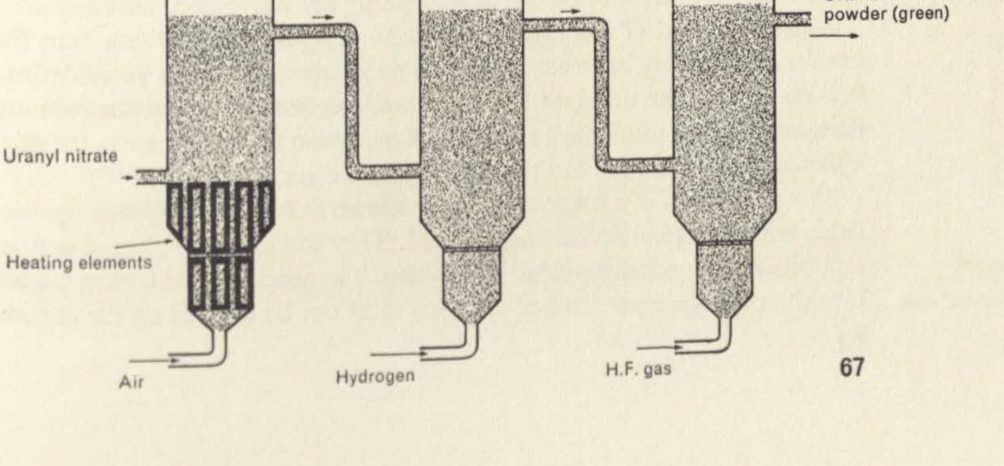


Fig. 50

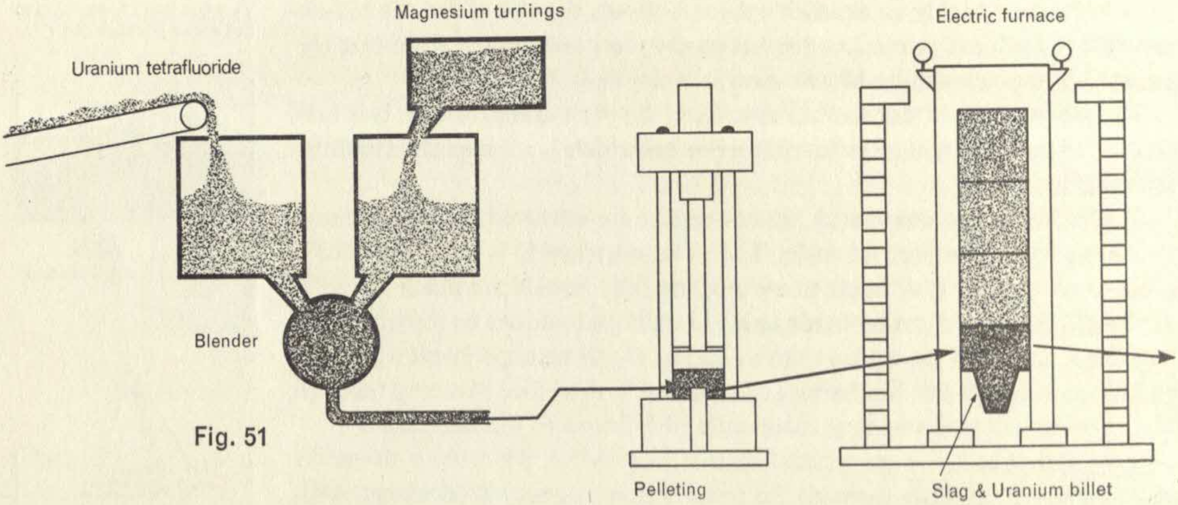
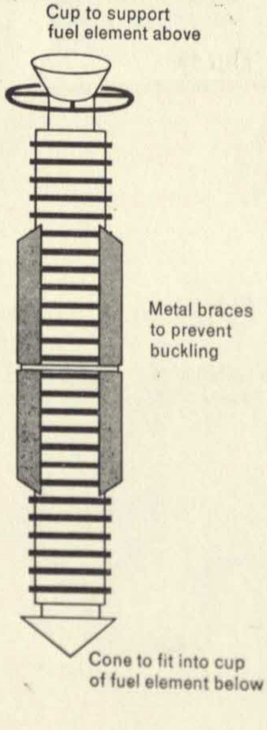


Fig. 51

Fig. 52
A Calder Hall type of fuel element. It is 42 inches long and weighs 30 lbs.


Cup to support fuel element above
Metal braces to prevent buckling
Cone to fit into cup of fuel element below

In order to get the pure uranium out, the green uranium tetrafluoride powder is mixed thoroughly with magnesium turnings and compressed into pellets. These pellets are then put into an electrically-heated furnace. Once the temperature has been raised to a few hundred degrees Celsius a chemical reaction occurs which itself produces more heat until the pellets are nearly white hot. At such temperatures the dense uranium metal which is formed in the chemical reaction melts, and collects at the bottom of the furnace with a slag of magnesium fluoride on top of it. When it has cooled the furnace is dismantled, the uranium taken out, and the slag cleaned off (Fig. 51).

A sample of the metal is taken for analysis in the laboratories. This sampling of the uranium is most important, since the presence of even the smallest quantities of elements such as boron or cadmium which absorb neutrons strongly, would seriously affect the performance of the fuel in the reactor. Even only a few parts in a million of these elements cannot be tolerated. The large-scale production of metals to such purity has never been done before.

This is the end of the chemical process at Springfields. From here the uranium metal goes back along the second production line to be made into fuel elements. The uranium is melted and cast into rods, and the rods are then heat-treated to minimize the risk of distortion when they are in the pile. They are also machined to the correct diameter and length.

The cans, made of a magnesium alloy known as Magnox, arrive at Springfields with the spiral fins already shaped. They are carefully cleaned and an end piece automatically welded in position. The uranium rod is then loaded into the can. Since particles of uranium must not be allowed on the outside of the can (they would make the coolant radioactive) the rods are not kept in the same room as the cans. An operator feeds a rod through a hole in the wall straight into a can held ready on the other side. The other end cap is then welded on as before. The completed can is squeezed on to the uranium rod to make sure that the heat will be conducted from the rod to the can when it is in the pile.

Metal braces are then welded round the middle of the can to prevent it buckling when it is in the pile (Fig. 52). Finally, after further cleaning and tests to make quite sure the can will not leak, each fuel element is packed in a polythene bag ready for transport to the reactor (Fig. 53).

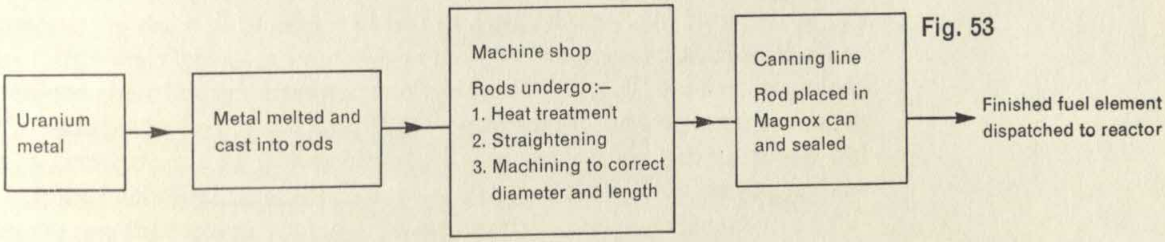

Uranium metal
Metal melted and cast into rods
Machine shop
Rods undergo:–
1. Heat treatment
2. Straightening
3. Machining to correct diameter and length
Canning line
Rod placed in Magnox can and sealed
Finished fuel element dispatched to reactor

Fig. 53

Chapter 12

Using nuclear power

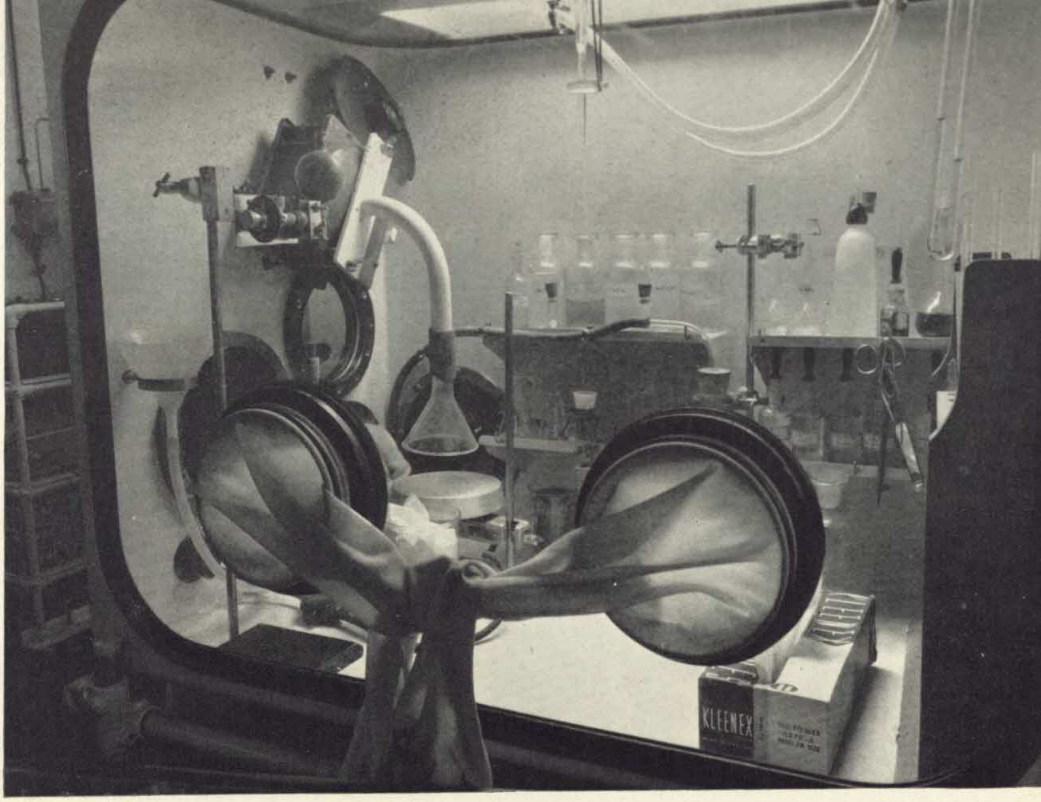
How can the power from nuclear reactors be used? The main practical use so far has been to produce electricity. Here a nuclear power station scores over conventional power stations in several ways. A conventional power station uses coal to produce steam, whereas a nuclear one uses the energy liberated by the fission of uranium 235 nuclei. This means that a conventional power station must always be built near a coalfield or where large quantities of coal can be delivered (e.g. near a river), so that its stocks of fuel can be replaced easily. The nuclear station can be built anywhere where a sufficient supply of cooling water is available. The Hinckley Point power station will use 35 000 000 gallons of water per hour for the steam condensing plant. Its fuel supplies will last about 4 years and so frequent replenishing will be unnecessary. The nuclear power station, as it were, carries it own portable coalmine with it.

The nuclear station has disadvantages though, notably the high cost of the initial equipment—fuel, moderator, shielding, heat exchangers, and so on, and the elaborate precautions necessary to avoid an accident. This last means that the station has to be situated away from densely populated areas. Another factor, easy to miss at first sight, is that of fuel supplies. Unless a country has natural sources of uranium it must buy its nuclear fuel from abroad. This brings politics into it, for if relations between a country and its supplier of fuel were to break off, and unless sufficient stocks of uranium had been stored, it could no longer operate its nuclear power stations, industry might be brought to a standstill with subsequent economic disaster. This is particularly important in Britain where the demand for power by both industry and the private consumer is increasing rapidly. We are fortunate in that Commonwealth countries such as Canada and Australia have large natural sources of uranium.

Great advances have also been made in the use of nuclear reactors for transport. Though here again the nuclear energy is used to produce steam which drives an ordinary turbine.

The first such application has been in ships. The American submarine *Nautilus* was the first ship to be powered by a nuclear reactor. Launched in January 1955, she travelled nearly 60 000 miles on her first charge of fuel—about 8 lb of enriched uranium. To cover the same distance using diesels she would have used three million gallons of oil. Three years later in 1958 she travelled under the North Polar ice cap. The *Nautilus* was submerged for 63 hours and travelled 1 830 miles under the ice. An even bigger feat was performed in 1960 by her sister ship *Triton*. She travelled round the world

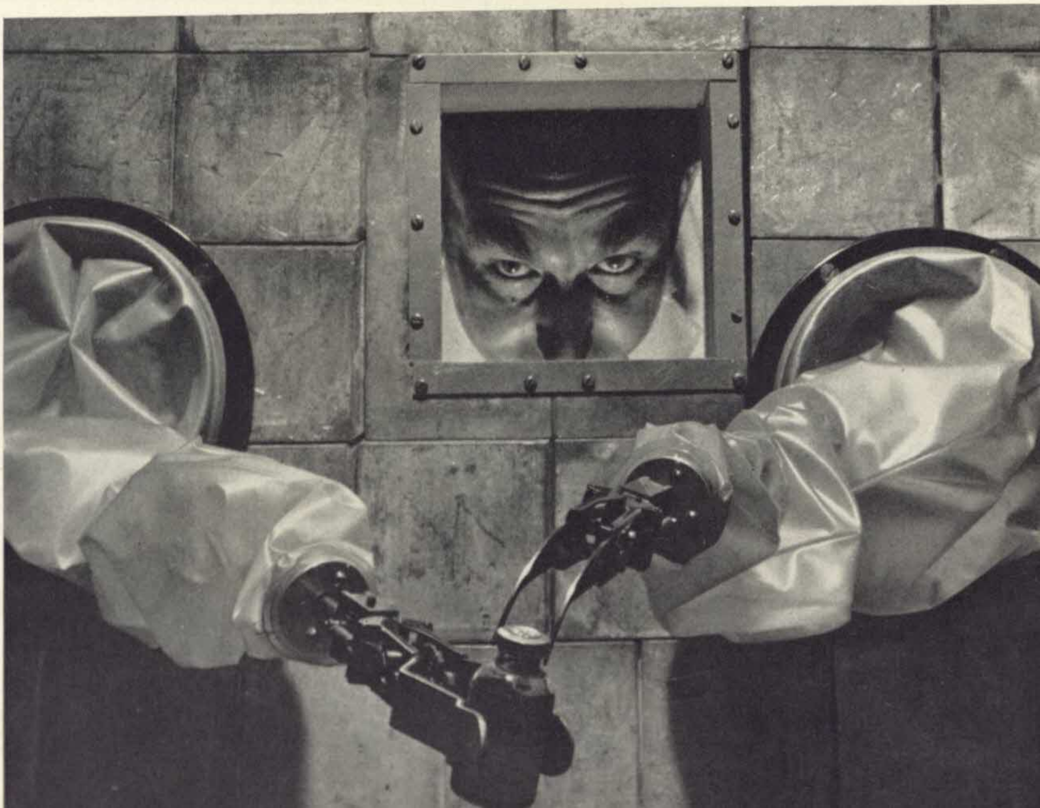
Plate Ia



A glove box. The double thickness plastic gloves can be seen tied loosely together in the centre of the picture. The U-tube, top right, shows that the pressure inside the box is slightly less than that outside so that all leaks are inwards.

The remote handling of radioactive isotopes from behind a lead brick wall. The man is looking through a lead glass window and the bottle contains radioactive gold 198.

Plate Ib



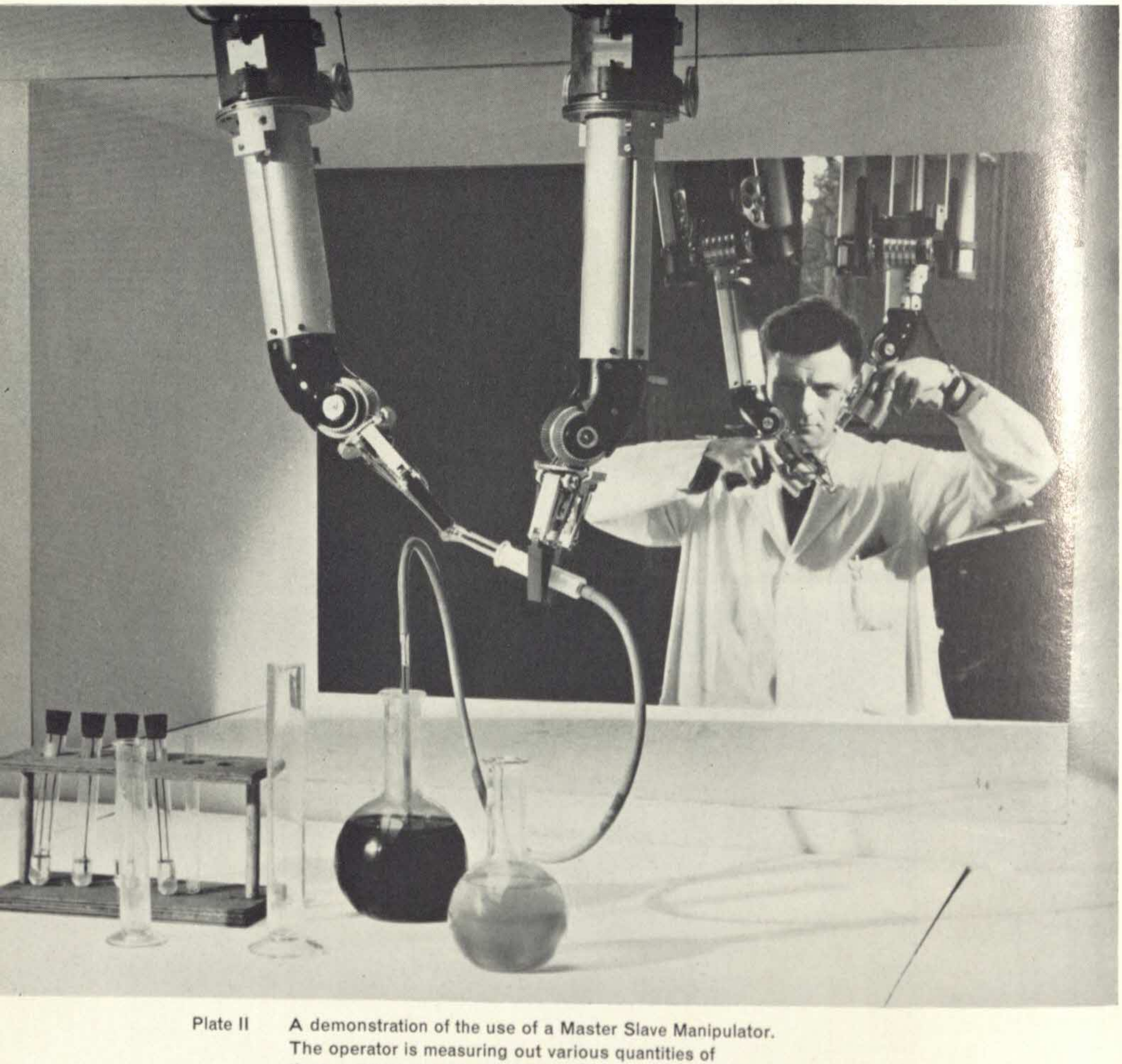


Plate II A demonstration of the use of a Master Slave Manipulator. The operator is measuring out various quantities of the two liquids into the test tubes. The mechanical hands are so sensitive that they can be used to pick up a pin.

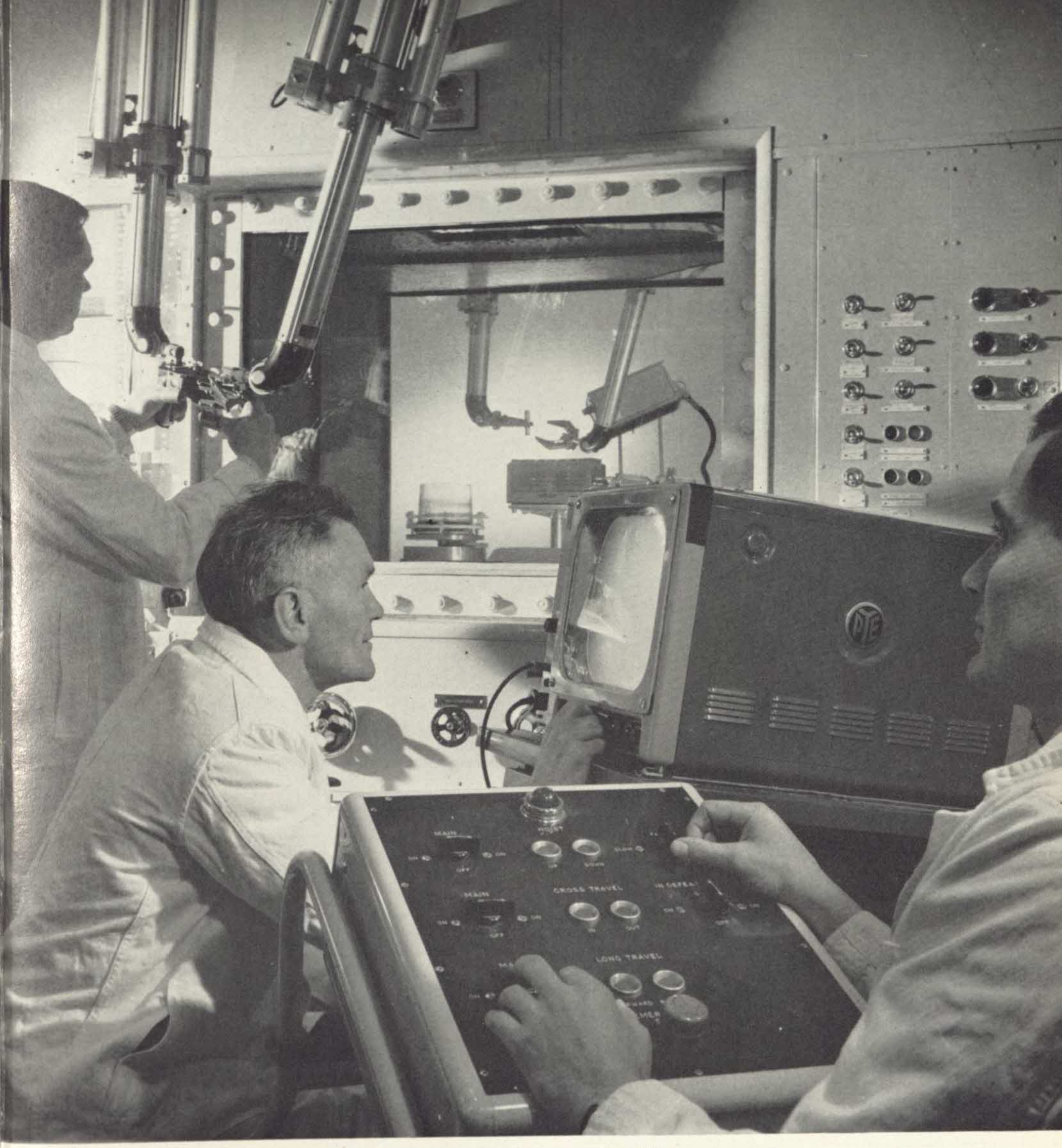


Plate III A Master Slave Manipulator being used in conjunction with closed circuit television at Dounreay. The engineers are examining and testing a sample of uranium from a fuel element used in the fast reactor.

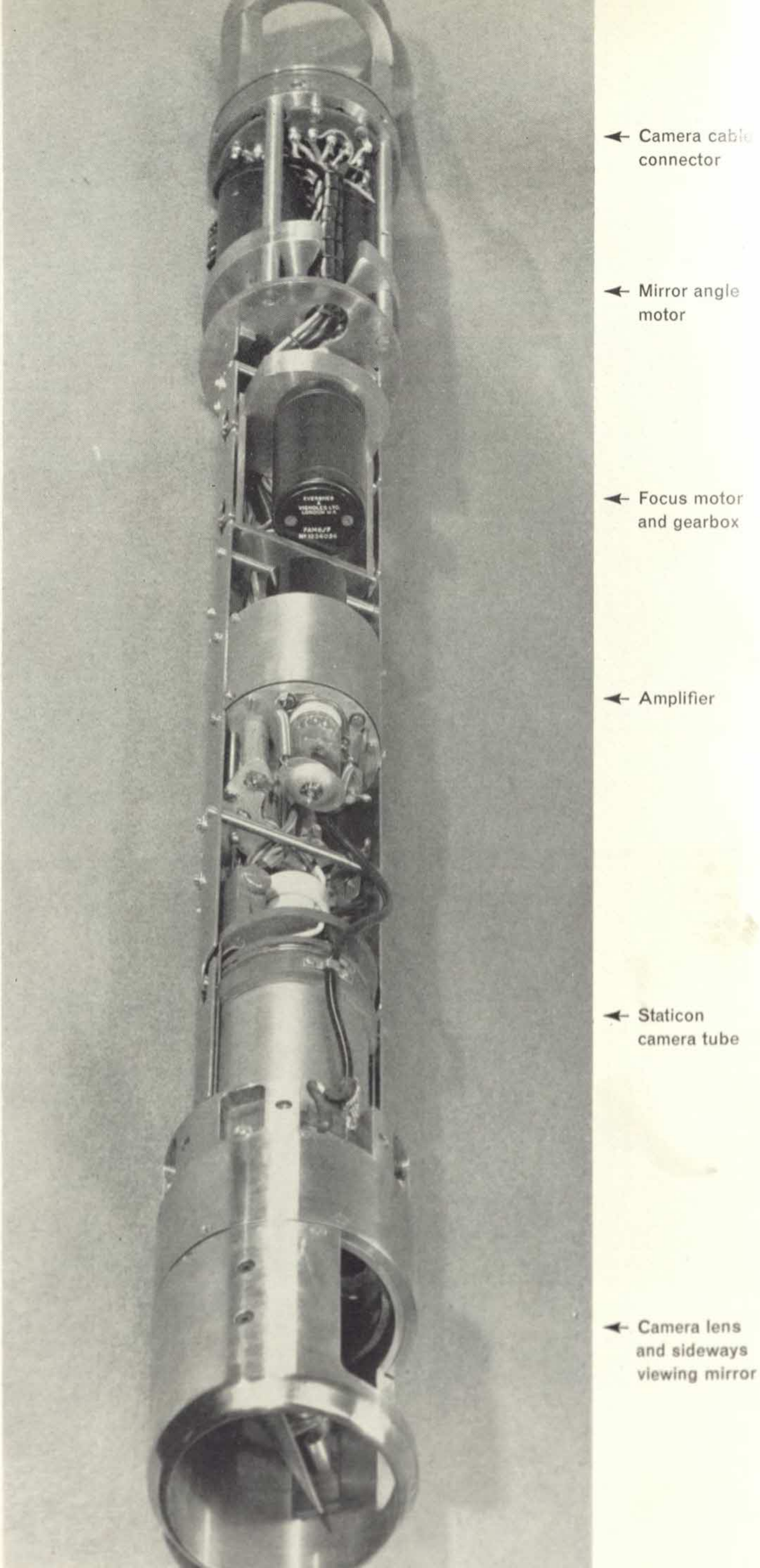


Plate IV

A reactor inspection television camera with its cover removed. It is 48 inches long and only 3·5 inches in diameter.

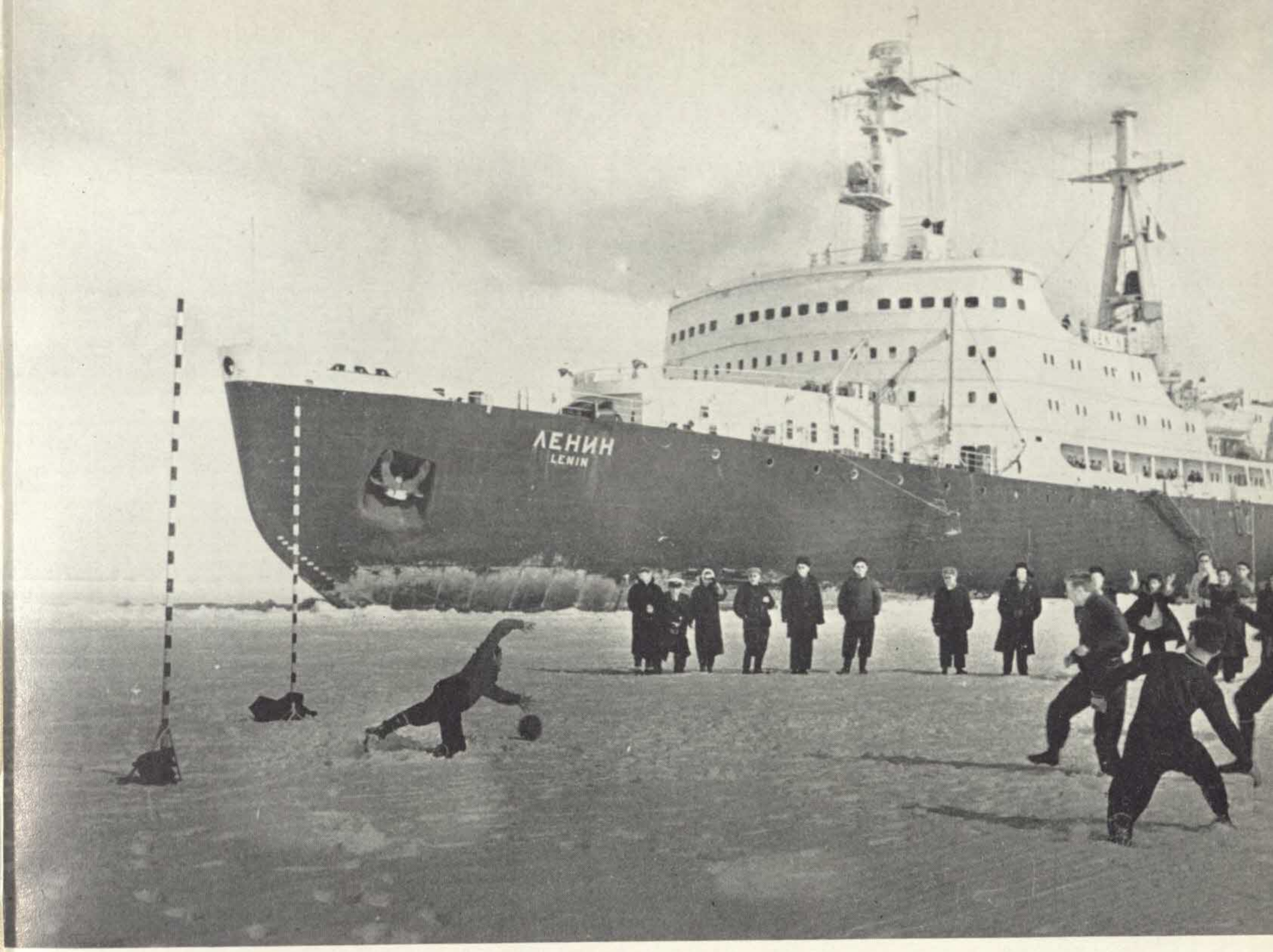


Plate V

The Soviet Union's nuclear powered icebreaker 'Lenin'. The fear of all sailors in ice bound waters is to be trapped by the ice and starve to death. The 'Lenin' can stay at sea for over a year without hardship. No luminescent scale instruments are allowed on board, to prevent the strict radioactive levels from being overstepped.

The lower photograph shows the senior engineer at the control board for the 'Lenin's' reactors.

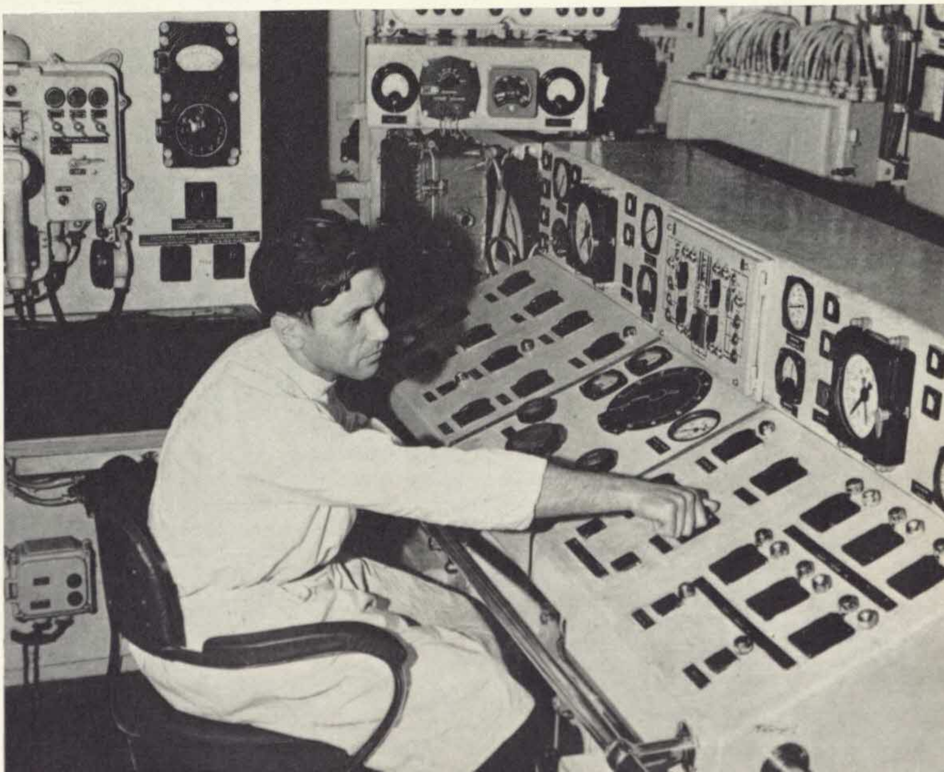


Plate VI A radioactive isotope being loaded into the wing tip of a B.O.A.C. Britannia.

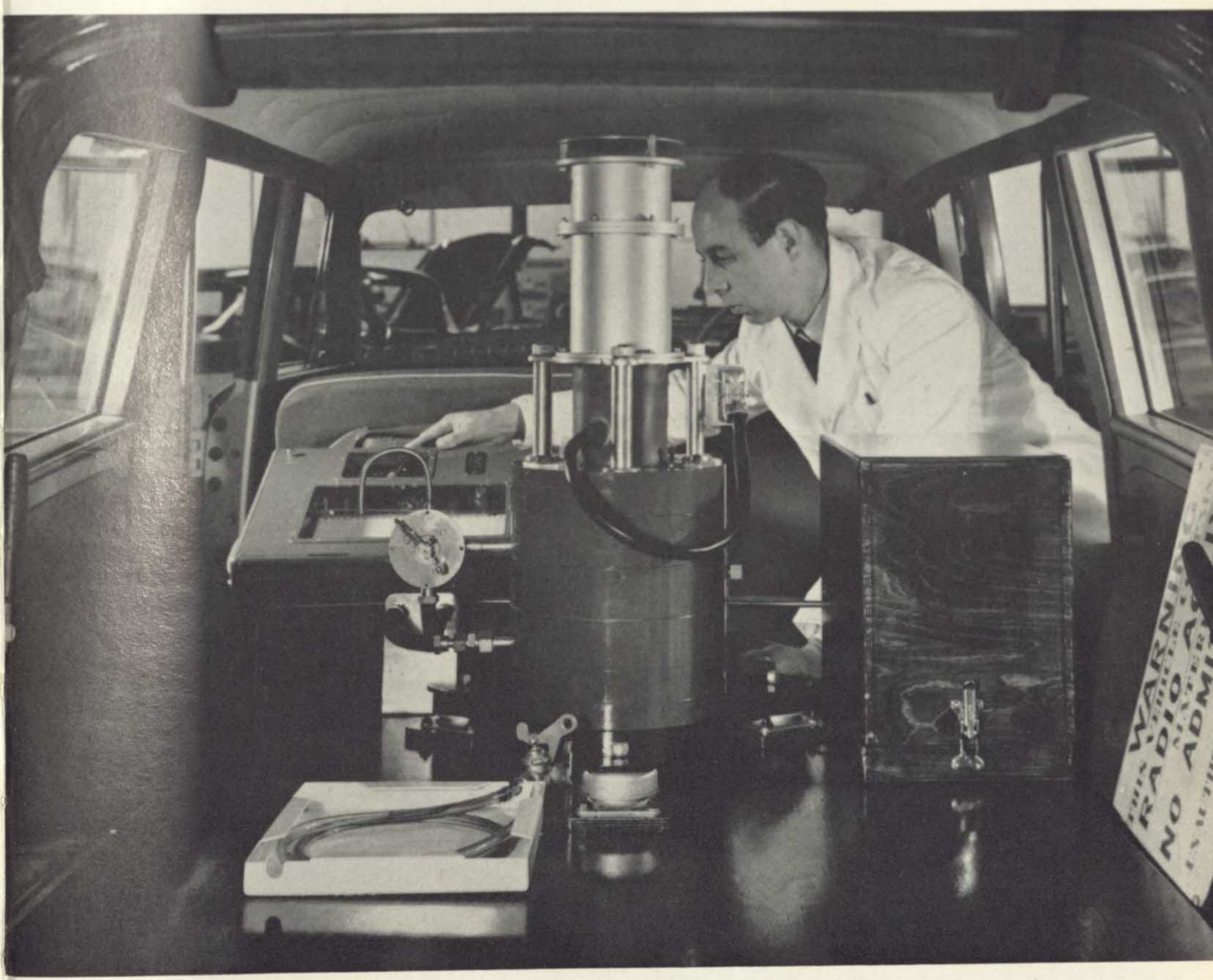
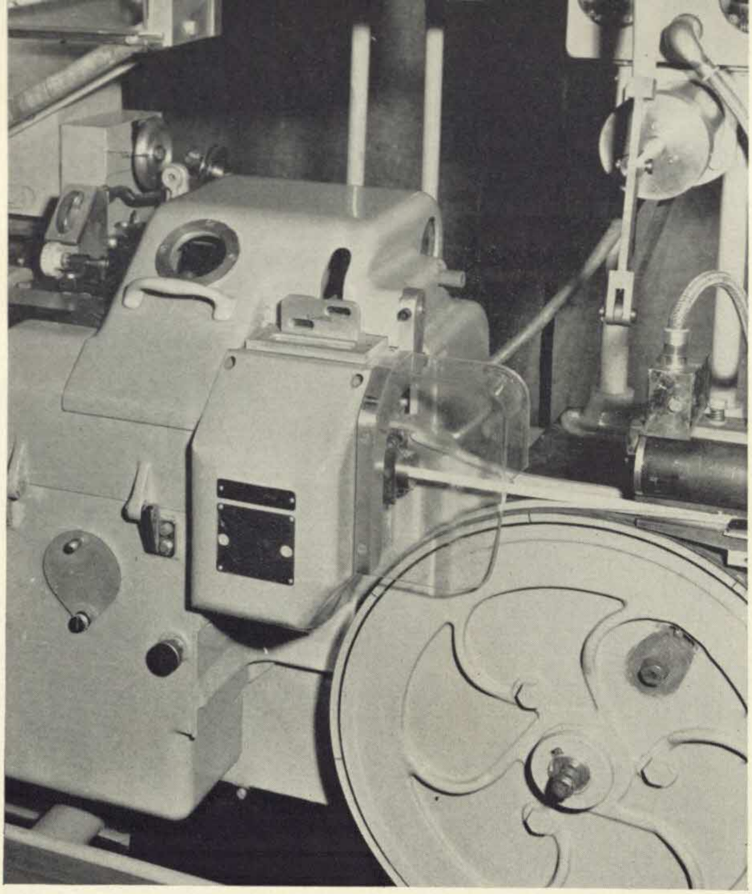


Plate VII Using radioactive isotopes to measure the wear of piston rings. The apparatus installed in the back of the car. In the centre is the scintillation counter surrounded by its lead shield to cut out unwanted radiation from other sources. The man is looking at the recording unit.



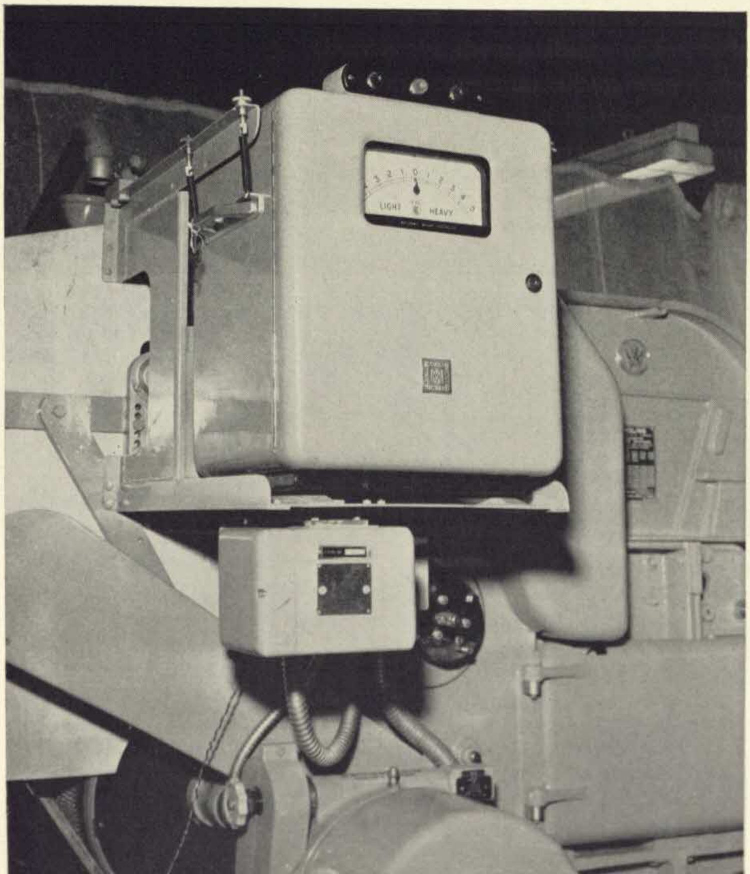


Plate VIII

The source and detector on a cigarette making machine. The cigarette rod coming off the top of the wheel is moving from right to left. After the weight of the rod has been checked it is cut into separate cigarettes.

The signal from the detector records on this meter whether the rod is light, heavy or of the correct weight. The hopper feeding tobacco to form the cigarette rod is automatically adjusted accordingly.

submerged. With a crew of 150 and powered by two nuclear reactors she took 84 days to complete the 36 000 mile voyage.

The American N.S. *Savannah* (maiden voyage February, 1962) is the world's first nuclear powered passenger cargo boat. N.S. stands for Nuclear Ship and she was given the name *Savannah* after the first steamship to cross the Atlantic. Fig. 54 shows the arrangement of the reactor and driving mechanism. The reactor has water under pressure acting as both coolant and moderator for the uranium oxide fuel. The *Savannah* has a displacement of 22 000 tons when fully loaded, carrying a cargo of some 10 000 tons in addition to 60 passengers and a crew of 110. She can cruise at a speed of 21 knots.

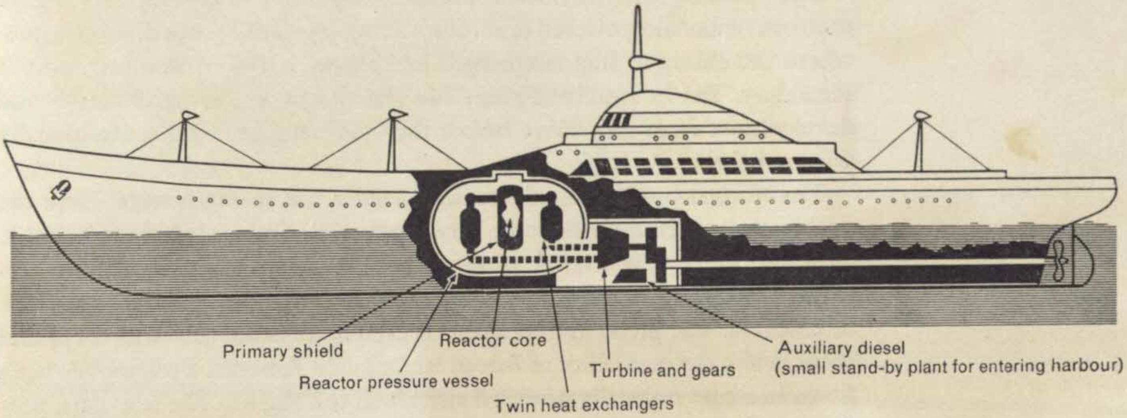


Fig. 54
The United States nuclear powered ship *Savannah*.

The Soviet Union's icebreaker, *Lenin*, is also powered by a pressurized water reactor, Plate V. The *Lenin* can move through ice floes 7 feet thick at a speed of 2 knots, or in clear sea at 18 knots. The Russians can therefore keep free the 6 000 miles of seaway north of their territory, for the *Lenin* does not always have to keep returning to port for refuelling: she can stay at sea for a whole year if necessary.

Already plans have been made for nuclear powered cargo-carrying submarines. Travelling at a depth of 300 feet such a submarine freighter would miss the storms and high winds which delay surface craft, and could pass underneath obstructions such as ice floes. With a speed of 25 knots, submarine freighters could keep open the route from Britain to ports in the Canadian North during winter when surface vessels cannot move because of the ice.

Provided adequate precautions are taken there is no fear of radiation hazards at sea. Naturally, the problem is more difficult than with land-based reactors. In the design of sea-going reactors the worst possible accidents have been imagined and provision made so that little or no radioactive materials would escape should such an accident occur.

The first of these is the danger of collision. Unfortunately this is most likely to occur in ports and narrow waterways where the population is likely to be high, and therefore the results of radiation leakage could be very serious indeed. This hazard is removed by placing the reactor deep inside the hull of the vessel. Even in the worst possible collision, where the ships hit perpendicular to each other amidships, the steel vessel which contains the reactor would be untouched. To reach this containment vessel in the *Savannah*, a ship would have to penetrate 17 feet. If the ship sank owing to the collision the containment vessel would keep dangerous radioactive material safely inside it.

The operating costs of nuclear powered ships are still considerably higher than conventionally powered ones. With military projects, such as submarines, where the ability to stay submerged indefinitely is the main object, cost is secondary. But in merchant ships like the *Savannah* further research and development must take place before they can compete with conventionally powered ships.

The nuclear propulsion of aircraft is still in the research stage. Here the problems are even more difficult. The reactor will obviously have to be made light enough for the aircraft to take off. This means the discovery of new methods of shielding the reactor since at the moment this involves many tons of concrete. The problem of collision is even more acute than with ships and there is also the possibility of forced landings. In America a reactor has been flown in a conventionally powered aircraft on test flights. The tests have provided information on methods of shielding the crew and equipment against radioactivity under actual flight conditions. However, there are still many problems to be solved before a nuclear powered aircraft is a practical proposition.

The necessity for adequate shielding and the unfortunately large number of collisions on the roads of today make the possibility of a nuclear powered car remote.

A nuclear reactor can also be used to make radioactive isotopes. The uses of these important products are so numerous and varied that we must treat them separately. They save industry millions of pounds each year.

Chapter 13

Making radioactive isotopes

GOLD can be made by bombarding mercury with neutrons. The only snag is that gold made in this way is much more expensive than ordinary gold. At the Atomic Energy Research Establishment at Harwell similar methods are used to make radioactive isotopes. In their way radio-isotopes are much more useful than gold. The use of radio-isotopes saves British industry between £3 500 000 and £7 000 000 annually. In American the figure is £200 000 000 and increasing every year.

The use of these radio-isotopes is not new. It began, using a naturally occurring radium isotope as long ago as 1913. What is new is the scale on which radio-isotopes are now produced and used. In 1913 it was a single delicate laboratory operation. Now radio-isotopes are produced on a large scale. For each of the last few years the sales of radio-isotopes by the U.K.A.E.A. amounted to over £1 500 000 and over half of this came from exports. These isotopes were sold to some 70 different countries, the principal buyers being Federal Germany, U.S.A., France, Canada, and Japan.

There are several sources of radio-isotopes. They may be the products of uranium fission, or of irradiation in a nuclear reactor; they may occur naturally, or they may be produced in a cyclotron, which is a machine for accelerating positively charged particles to high energies. Radio-isotopes are produced when elements are bombarded by these positively charged particles. By far the most radio-isotopes are made by bombarding the correct element with neutrons in a reactor. In many cases the required radio-isotope can be made in a single operation by irradiating the corresponding inactive element. This works for cobalt and gold, for example. The production of these radio-isotopes is therefore a matter of carefully planned routine.

When ordinary cobalt is put into the reactor each nucleus contains 27 protons and 32 neutrons, giving an atomic weight of 59. In the reactor these nuclei are bombarded by neutrons. Each cobalt nucleus absorbs a neutron and the result is nuclei which have 27 protons and 33 neutrons, giving an atomic weight of 60. Since the number of protons is the same the element is still cobalt, but it is now heavier than before—it is the isotope cobalt 60. The cobalt 60 changes back to cobalt 59 by the emission of gamma rays, and has a half-life of 5·3 years.

To produce the radioactive isotope carbon 14, nitrogen (in the form of aluminium nitride) is bombarded with neutrons in the reactor. The nitrogen nuclei absorb the neutrons to produce carbon 14 and protons:

$$_{7}N^{14} + {}_{0}n^{1} \longrightarrow {}_{6}C^{14} + {}_{1}H^{1}.$$

The longer the substances are left in the reactor the more nuclei are converted into the radio-isotope.

The main reactors at Harwell are fitted with special mechanisms for loading and discharging small 'targets' of these elements. Such irradiations are mainly done in a reactor called BEPO. When more intense irradiation is required reactors called DIDO and PLUTO are used. In the latter case the energy given up by the bombarding neutrons is so large that special targets have to be made. These are constantly cooled to take away the heat produced. Really intense irradiation can now be provided in the large power reactors up and down the country.

Some radio-isotopes can be used just as they come out of the reactor. But many need special chemical refining to separate them from the unchanged target materials, or in some cases from a complicated mixture of other radio-elements. Such chemical processing is carried out at the Radiochemical Centre at Amersham, Buckinghamshire. Here it is a matter of routine to separate radio-iodine, radio-phosphorus, and radio-carbon. The separation of other radio-isotopes is more difficult. It is still a matter for careful experimental technique, which, because of the danger from the emitted particles and rays, has to be performed in screened cells or glove boxes.

For the purpose of research and in the applications of these radio-isotopes it is often necessary to make specific chemical compounds which contain atoms of a radioactive element. In making these compounds which have been 'labelled' by radioactive atoms the chemists at Amersham have to be much more ingenious than the ordinary chemist. The ordinary chemist can obtain the compounds he wants from natural sources, for example benzene from coal, sugars and carbohydrates from plants. At Amersham the chemists have to make all these complex compounds starting from carbon dioxide, the carbon atoms of which are the active isotope, carbon 14. Not only is the job itself difficult for this reason, but carbon 14 is relatively expensive and therefore must be used carefully. Often the research for which the compound is needed specifies that the active atom must be placed in a certain position in the molecule. This means even more ingenuity from the Amersham scientists.

Sometimes it is too difficult to go through these complex processes by hand in the laboratory. It is easier and quicker to let a living organism do the job instead. In this case an organism is chosen which will produce the required labelled compound quickly and efficiently from carbon dioxide. Labelled sugars and starch are made by photosynthesis in the green leaves of canna or tobacco plants. Photosynthesis is the building up of compounds by the action of light. Under the action of sunlight the green leaves of the plant are able to convert the activated carbon dioxide and water into sugar and starch. The required labelled compounds are then separated out from the leaves.

Even when the radio-element has been produced the work at Amersham is not finished. The radio-isotope must be placed in a container suitable for the work it has to do.

It may be in the form of a fine needle for use in medicine, or a specially designed container made of thin aluminium foil for use in some research project. These containers then have to be suitably packed and dispatched to the customer. For example, a large cobalt 60 source for use in a hospital emits such powerful gamma radiation that it has to be packed in a container the height of a man and weighing 8 tons. Even so the outside of the container is noticeably hot to the touch. On the other hand carbon 14 can be put into a hermetically-sealed can and sent by post quite safely.

Every radioactive isotope has its own characteristic half-life. For the radio-isotopes sent out from Amersham this half-life varies greatly—from about 15 hours for sodium 24 to about 5 500 years for carbon 14. This means that large stocks of carbon 14 can be kept and dispatched by post, or by sea if the consignment is for abroad. The short-lived isotopes present a more difficult problem. With sodium 24 for example, half the radioactive atoms you start with have decayed after only 15 hours, after another 15 hours only a quarter of the original amount is left, and it keeps on decaying all the time. Such radio-isotopes can only be used within easy reach of Harwell where they can be delivered by fast car or motor cycle. At the Brookhaven National Laboratory in America the medical centre is right alongside the reactors. By means of pneumatic tubes short-lived isotopes such as chlorine 38 (half-life 37 minutes) can be administered to patients only fifteen minutes after removal from the reactor.

Radio-isotopes with a half-life of a week or more are delivered by air to all parts of the world, Plate VI. The latest Comet IV's and Britannias of B.O.A.C. and B.E.A. are fitted with special wing-tip containers for radio-isotopes. In this way orders can reach North America in one day, and Japan or Australia in two days.

When a customer buys a radio-isotope he buys, say, radio-sodium with a certain activity. So that he will actually receive a source of this activity the Radiochemical Centre allows for the amount which decays during transit. When the source leaves Amersham or Harwell it will be stronger than the source ordered, but the decay during the journey will make it exactly right when it reaches the customer.

The use to which the customer puts the radio-isotopes naturally depends on his particular requirements. We will look at some of the uses in the next chapter.

Chapter 14

Radioactivity in everyday life

THE toothpaste you used after breakfast this morning was probably packed with the aid of radioactive isotopes. It is important at the factory to see that every tube contains the correct amount of toothpaste. Fig. 55 shows how this is done. Partially filled tubes are automatically rejected so that they are not sent out and sold by mistake. By using this method the customer knows he is getting full value.

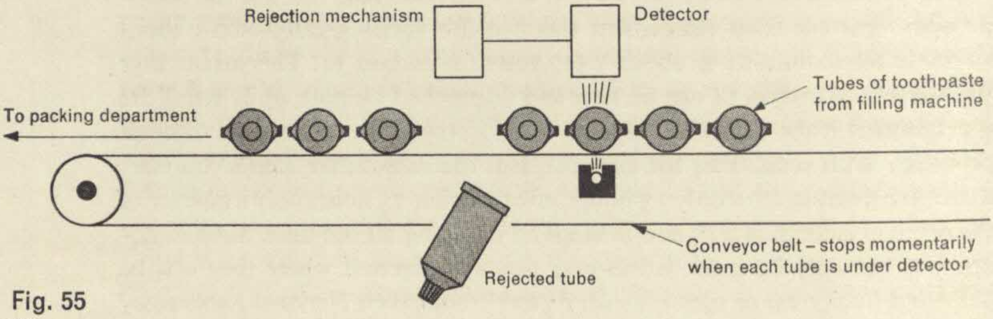

Rejection mechanism
Detector
Tubes of toothpaste from filling machine
To packing department
Conveyor belt – stops momentarily when each tube is under detector
Rejected tube

Fig. 55
Checking the filling of toothpaste tubes. The tubes are filled in the upright position, tail end up, any air pocket due to a light fill is left in the tail end. Any tube with such an air pocket is detected as shown in the diagram and subsequently rejected.

This is just one example out of the hundreds of uses of radio-isotopes. The usefulness of radio-isotopes follows from two facts. First, that the isotope behaves in exactly the same way as the stable element, and second, that the position of these radioactive atoms can be followed by detecting the particles and rays they give off. Thus in any reaction the activated atoms always behave in the same way as the unactivated atoms but signal their presence. Experiments using radio-isotopes are often called tracer experiments, since it is easy to trace the whereabouts of the activated atoms. Besides acting as signals in this way the particles and rays given off are useful in their own right. Here are some specific examples of the ways in which radio-isotopes are used.

Wear in engines

Tracer atoms have made possible easier and more realistic studies of the wear of piston rings in motor car engines. This had led to improved lubricating oils. Normally the piston rings have to be run in the engine for many hours and then the engine dismantled, the piston rings removed and tested for wear. If further experiments have to be done the rings have to be re-fitted and the engine re-assembled. This inevitably leads to variability in the results obtained.

By making the piston rings radioactive, continuous testing can be carried out under actual road conditions and without ever having to dismantle the engine. Fig. 56 shows how the apparatus is fitted into the car under test. As the radioactive piston rings move up and down in the cylinder tiny bits are worn off and are carried away by the lubricating oil. These tiny bits will still be radioactive and the amount appearing in the oil will be a measure of the amount of wear. The oil is therefore pumped to the back of the car. Here a scintillation counter detects the amount of gamma emission from the oil and this is recorded on the unit provided. Plate VII shows the equipment in the back of the car. The amount of gamma emission is proportional to the concentration of radioactive material in the oil and it is therefore proportional to the piston ring wear. This method can detect amounts of wear fifty times less than was possible by previous methods. The results of these radioactivity experiments showed that on increasing speed from a steady 30 m.p.h. to a steady 40 m.p.h. the rate of wear was approximately doubled; and at 50 m.p.h. the rate of wear was about three times that at 30 m.p.h.

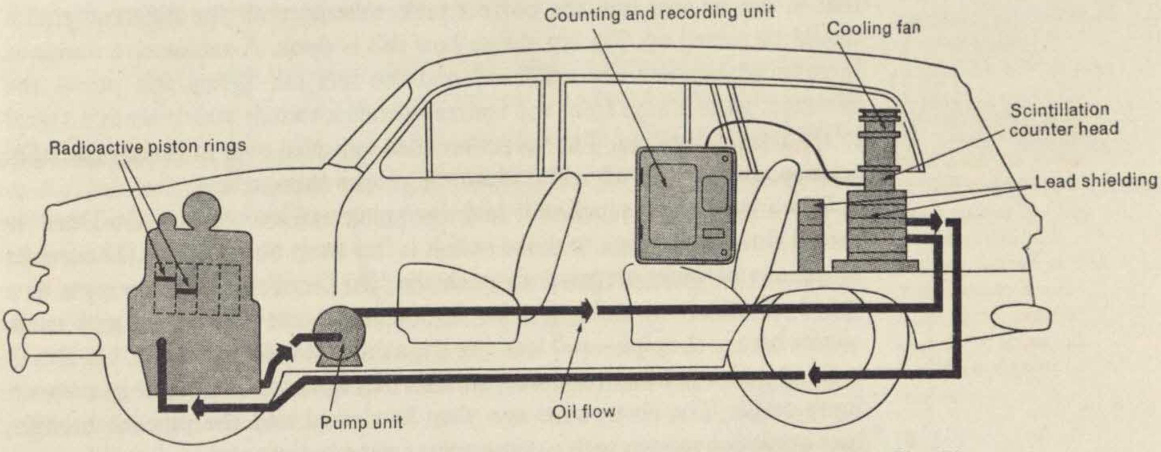


Fig. 56
The testing of piston ring wear showing how the apparatus is arranged in the car.

Mixing substances in industry

In industry the mixing of substances in exact proportions is common practice. The problem here is how to get an even mix, especially when a very small quantity has to be mixed with a very large one. The mixing of paints and making of glass are two such examples. A third is the addition of various elements and vitamins to animal foodstuffs. It is necessary, for example, to include a trace of manganese in pig food. This helps the formation of bones and makes strong animals. About a dessertspoonful of manganese sulphate has to be mixed with every two tons of the food. How can the manufacturers make sure that there is an equal amount of manganese in each sack of food sent out? This problem was solved by putting the manganese sulphate in a reactor for a few seconds to make the manganese weakly radioactive. The food was mixed with this active manganese sulphate and each bag checked using a scintillation counter. Different methods of mixing were tried until the counter showed the same activity from each bag, and thus that the manganese had been mixed evenly. The radioactivity is so weak that it has disappeared long before the food reaches the animals.

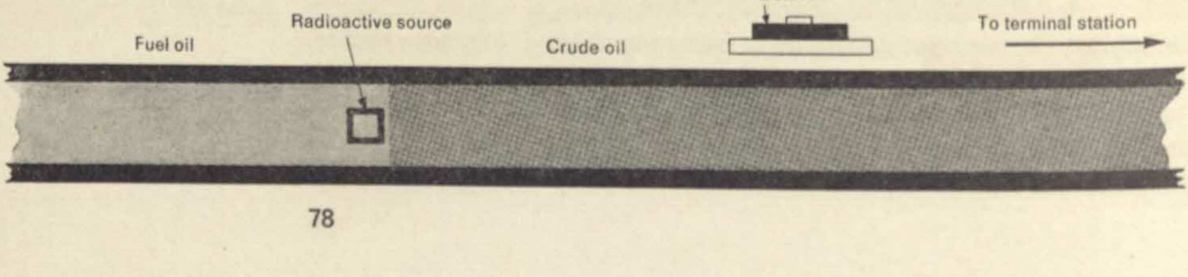
Oil

Radio-isotopes also find a variety of uses in the oil industry. At the refinery radio-isotopes are used to follow the flow of oil in the pipe lines. One pipe has different grades of oil pumped through it from the docks to the storage tanks. It is important to know exactly when a new batch of oil is coming through so that it can be sent into the correct tank, otherwise all the different grades would be mixed up. Fig. 57 shows how this is done. A radioactive source is introduced between the crude oil and the fuel oil. When this passes the detector, gamma rays from the source operate a switch which sends a signal to the terminal station. The valves are then switched over at exactly the right time so that the fuel oil will go into the proper storage tank.

When the new oil pipeline is laid a scraping tool known as a 'Go-Devil' is forced through the pipe to make sure it is free from obstructions. Thousands of gallons of water are used to push the 'Go-Devil' through the pipe at a speed of about two miles per hour. Sometimes the 'Go-Devil' gets stuck somewhere in the pipe—and locating it is a difficult task. When the 'Go-Devil' is fitted with a radioactive source, suitable detectors can determine its position more easily. The obstruction can then be cleared and the pipeline brought into operation sooner, with a consequent saving in time and money. The same technique is used in the cleaning of pipelines which have been in use for some time.

Fig. 57

Signalling the arrival of different grades of oil.



Testing castings and welds

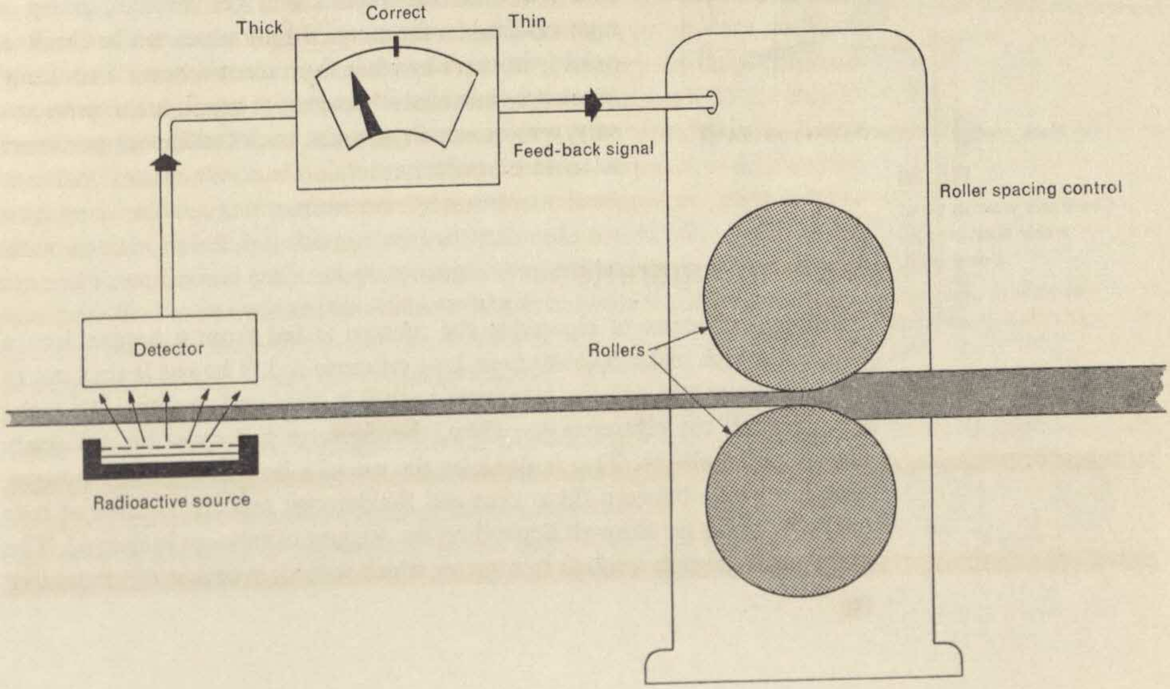
Gamma ray sources also have extensive applications in the detection of faults in castings, and in the testing of welds. Previously this type of work was done only by means of X-rays. Even portable X-ray units are quite cumbersome and can only test steel up to 2 inches thick. Similar gamma ray sources can test steel up to 8 inches thick. The part to be examined is placed between the source and a photographic film. Thus the intensity of the rays reaching the film is reduced by the metal parts. Parts of the metal which are thinner than they should be will let more of the gamma rays through, and so will show up darker on the film when it is developed. In a similar way other flaws such as hidden cracks can be detected by this method. The gamma source can be made quite small and can be used to test welds which are difficult to get at with normal X-ray equipment. Welds in pipelines can be checked in this way. The gamma source is placed at one side of the weld and the film on the other. This testing of welds in the field is only possible because of the portability of the equipment and saves many hours of laborious testing by other methods.

Thickness control

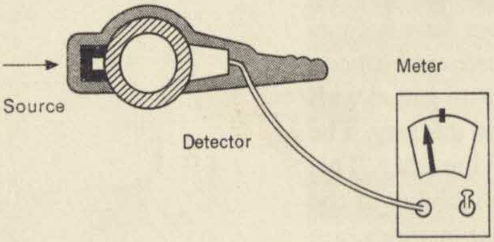
Radio-isotopes are also used to regulate the thickness of metal or paper sheets as shown in Fig. 58. The radio-isotope in this case is a beta emitter. The thicker the metal the more beta particles are absorbed and the lower the reading on

Fig. 58

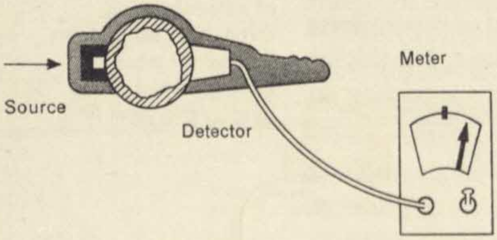
Regulating the thickness of rolled sheets of metal. This method can be used for other materials which are produced in sheet form.



the detector. For thin sheets more beta particles get through and the reading on the meter is correspondingly higher. By using a carefully measured thickness of the metal the correct reading on the meter is noted. If the reading is above this the sheet being rolled out is too thin, if below it is too thick. The meter is usually coupled to the mechanism which controls the rollers producing the sheet. When the meter records that the sheet is too thick, an electrical signal is fed back to the rollers to make them go closer together. This feed-back principle is very important and ensures that the sheet is kept at the correct thickness.



(a) Meter reading indicates that the pipe is serviceable



(b) Meter reading indicates that the pipe is worn

Fig. 59
Checking wear in pipes while they are still being used.

Before this method was used, samples of the sheet had to be taken, measured, and then the rollers adjusted accordingly. This took time and quite a large amount of the metal sheet had been rolled out while the testing was taking place. If the thickness was found to be wrong the whole sheet had to be made again. With the radio-isotope and feed-back technique the measurement and adjustment are made almost instantaneously. There is thus no wastage or stoppage in production.

A similar method is used to check the wear of pipes while they are still being used. The source is placed at one side of the pipe and the detector at the other as shown in Fig. 59. If the tube is worn there will be less material between the source and detector and so more beta particles than normal will get through, giving a high reading on the meter. Many pipes can be checked quickly in this way while they are still being used. Only absolutely essential stoppages for repair are then necessary, a most important point with continuous processes as in an oil refinery.

Making cigarettes

In the manufacture of cigarettes the tobacco is fed from a hopper into a machine which makes a continuous long cigarette rod. The rod is then cut to the correct lengths and the cigarettes packed in tens and twenties. To make sure that all the cigarettes are alike, the cigarette rod must be uniformly packed with tobacco. This is done by the use of a beta active radio-isotope. The rod passes between the source and the detector and the number of beta particles which get through depend on the amount of tobacco in the rod. The detector then sends a signal to a meter which records whether this measured weight of tobacco is correct, heavy, or light. This signal is amplified and fed back to the hopper control mechanism to correct the tobacco feed. If the rod is too light for example, the feed-back signal makes the hopper feed more tobacco into the cigarette rod to make it the correct weight. Plate VIII shows a cigarette machine fitted with this method of automatic control.

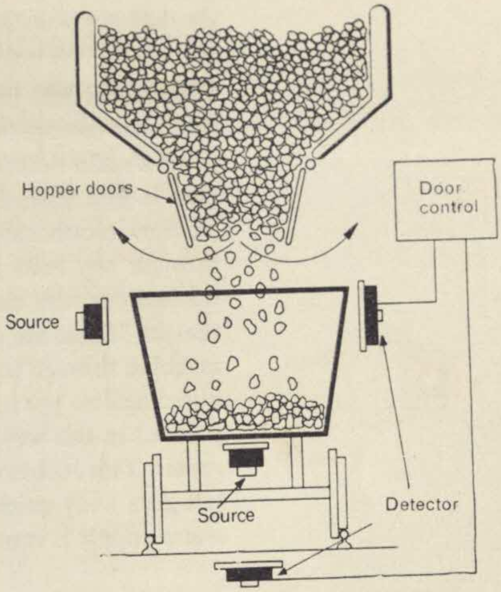


Fig. 60
Hopper door control.

Automatic level controls

Fig. 60 shows another type of automatic control. When the truck is directly beneath the hopper doors the gamma rays from the cobalt 60 source under the truck operate a switch connected to the detector. This operates the door controls and the hopper doors open. When the truck is full the gamma rays from the other source will be cut off, and a switch coupled to this detector closes the hopper doors again.

Often it is difficult to regulate the level of liquids either because they are corrosive or because they have to be kept at very high temperatures. Under these conditions ordinary level indicators, such as floats, cannot be used. This problem is easily solved by again using the gamma rays from cobalt 60. Fig. 61 shows exactly how it is done. The liquid absorbs the gamma rays so that they cannot reach the detectors. Thus when the level gets too low, the gamma rays trip the low level alarm and the motorized valve pumps more liquid into the container. Should the level get too high, the gamma rays from the top one of the two sources are cut off, this operates the high level alarm and the motorized valve automatically closes. The cost of the gauge may well be saved by preventing one overspill of the hot or corrosive liquid. Such an overspill would block and damage pipes and equipment fitted to the top of the container, and these would cost quite a lot to clean out and possibly replace, to say nothing of the time lost while this was being done.

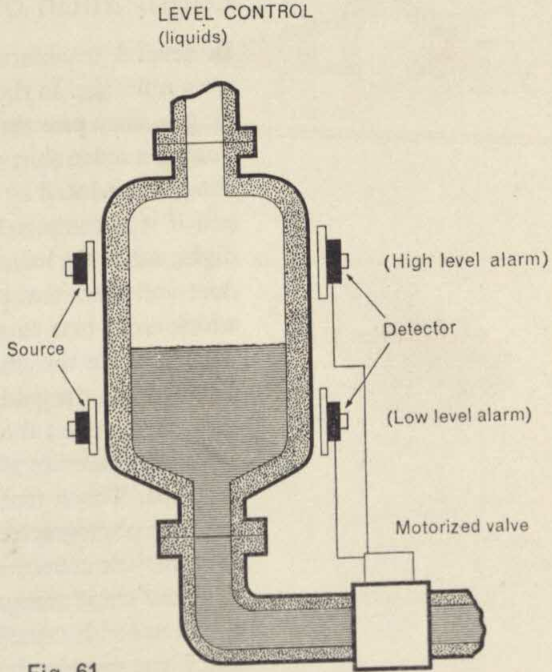


Fig. 61
Liquid level control.

Leak detection

Undetected leaks from underground water or oil pipes also cause wastage and can cause damage to surrounding land. Suspected leaks can easily be checked using a radio-isotope. Take the case of a water main suspected of leakage. The pipe is first washed out with water which contains radioactive baking soda (sodium bicarbonate with active sodium 24 atoms in it). This solution seeps through any leaks into the earth surrounding the pipe. The pipe is then washed out with clean water so that only the radioactive patches in the soil remain. These are then found by pulling a detector coupled to a recording machine through the pipe. All increases in the count rate of the detector are noted against the length of cable played out. Once the leaks have been pinpointed in this way, workmen can dig down to the exact spot and make the repair. This is obviously particularly important in built-up areas. Any activity left goes away quickly so that there is no danger of contamination when the water supply is turned on again.

Elimination of static electricity

In several manufacturing processes electric charges produced by friction are a nuisance. In the weaving of fabrics the fibres become electrified by rubbing as they pass through the loom. You can see this effect quite clearly by pulling a nylon shirt quickly over your head when you take it off. The electric charges produced by your hair rubbing on the nylon can be heard crackling, and if it is completely dark you can sometimes actually see tiny sparks. At night, when the loom is not working, these static charges on the fabric attract dust and leave that part of the fabric dirty. To prevent this a small source which emits beta particles is exposed when the loom is shut down each night. This removes the charge on the material in the same way as the charge is removed from the gold leaf electroscope mentioned on p. 18. With no electric charges to attract the dust a much cleaner fabric results.

Plastic materials also pick up static electric charges when they are being polished. This is true of any polishing process, in particular the polishing of accurate photographic and optical lenses. The use of a beta active source again prevents the collection of dirt.

These static charges also limit the output of newspaper printing presses, where speed is essential. The static charges cause the paper to jump slightly and if the machine is run too fast these jumps cause the paper to break. One installation which would be capable of printing 45 000 newspapers per hour is limited to 25 000 per hour for this reason. Elimination of the static charges by means of a radio-isotope is yet again the answer.

These practical uses of radioactive isotopes show what a large contribution they are making to our everyday life. They have enabled problems to be solved easily and quickly where previously a solution seemed impossible.

Chapter 15

Radioactivity in research

Archaeology

MANY scientists have found the use of radioactivity very valuable in their research work. At the Research Laboratory for Archaeology and the History of Art, in Oxford, such a method has been used to examine Greek silver coins over 2 000 years old.

The coins were first put into a reactor at Harwell and bombarded by neutrons. This made the coins radioactive—they emitted gamma rays. Each impurity in the silver coins emits gamma rays of a certain energy, so by measuring these energies the different types of metal in the coins were found. This was done using a scintillation counter. In addition to this the amount of radiation of each energy gives the amount of that particular element present. In this way it was found that silver coins from Athens contained 0·03 per cent gold and 0·05 per cent copper, while those which came from Corinth had 0·4 per cent gold and 1 per cent copper. This meant that the Athenians and Corinthians got their silver from different mines. Coins fifty years later than this had identical amounts of gold and copper, showing that the people of the two cities then obtained their silver from the same source.

Archaeologists also use a radioactivity method for measuring the ages of their specimens. The 'age' for an archaeologist is the time that has passed since the object was made, or if an animal, from the time it died. The method depends on the active isotope carbon 14 and is called radio-carbon dating. Cosmic rays from outer space convert nitrogen in the upper atmosphere into carbon 14. This radioactive carbon then combines with oxygen to form radioactive carbon dioxide. Plants take in some of this radioactive carbon dioxide with ordinary carbon dioxide in the usual way. Animals then eat these plants and so the radioactive carbon is taken in by them also. While the plants and animals are alive the amounts of radioactive carbon in them remains constant, since as some atoms decay they are replaced by new ones from outside.

When the plant or animal dies no new radioactive carbon atoms can replace those which decay. Thus the older the specimen the fewer the number of radioactive carbon atoms which will remain. On average, for 1 gram of carbon from a plant or animal which has just died the decay rate is 12·5 atoms per minute. When placed in a counter this specimen will therefore give an average reading of 12·5 counts per minute. The count rate is less than this for older objects. Since the half-life of carbon 14 is about 5 500 years, half the original radioactive atoms will still be left after this time; 11 000 years after the plant or animal died only a quarter of them will be left, and so on. Thus by measuring the count rate given by the specimen its archaeological age can be found.

Radio-carbon dating has some disadvantages though: part of the specimen has to be converted to pure carbon. If the specimen is wood a piece of it is burned. Archaeologists are naturally reluctant to do this with rare specimens which are small, since the removal of even a small piece would be obvious. Also radio-carbon dating can only tell us the age of objects up to about 40 000 years old. This is because after this time the amount of radio-carbon left in the dead organism is too small to detect by present methods.

A mammoth found in the ice of the Taimyr Peninsula in the Soviet Union was found to have lain there for some 12 000 years since it died. Such dates are not exact, indeed no archaeologist can quote dates exactly. They are always expressed as plus or minus so many years to show that the age of the object most probably lies between these two limits. The archaeological date for some excavations at Jericho was 7 500 ± 500 years. The radio-carbon date for the same excavations was 7 800 ± 160 years. The deepest excavations at Jericho show an age of some 9 000 years, making it the oldest known city in the world.

Biology

Carbon 14 has also been used to study the way in which plants convert carbon dioxide and water into food. This process is called photosynthesis. Until recently it was thought that, by the action of sunlight, plants converted the carbon dioxide and water into certain simple compounds. These were then built up into a form of sugar which is the basis of the plant foods known as carbohydrates. Carbon 14 has shown this to be incorrect. First, complicated compounds are formed which are then broken down to form the basic sugar molecules. Similar experiments have also shown that the carbon dioxide is also taken in by the roots and not just by the leaves.

Other fields of biological research have also benefited from the use of radioactive isotopes. By attaching a tiny amount of such an isotope to beetles their position can be followed using a counter. In this way the behaviour of the beetles can be studied much more accurately than before, as their movements can be traced even when they are underground.

These and many other applications show that radioactive isotopes are the most important tools in biology since the invention of the microscope.

Agriculture

Closely allied to biology is research in agriculture. Already radioactive isotope studies are yielding startling and very practical results. By adding radioactive phosphorus atoms to phosphate fertilizers the best way of feeding the fertilizer to different crops has been found. For example, a test field was planted with maize. In one area the fertilizer was spread evenly over the surface; in another at different depths in the soil; in another in holes at various points; and in yet another the fertilizer was introduced with the seeds of maize. Observations were then made with a small portable counter to detect when the radioactive phosphorus atoms first appeared in the leaves. This then gave the best way of feeding the fertilizer to the crop. For maize it is best to introduce the fertilizer with the seeds.

Similar experiments showed that the spraying of fruit trees with phosphate does not produce the best results. A better method is to put the fertilizer into holes about 2 feet deep near the roots.

Previous to this type of research it was thought that the sugar beet actually made sugar in its roots. Using radio-carbon, Russian scientists have shown that the sugar is made in the leaves of the plant and is then passed to the roots merely for storage.

Again, in the potato plant they thought that the starch-forming sugars were passed to the roots by a single channel. Radio-isotope studies showed that this was not so. Certain leaves supply certain tubers in the root system; cut off these leaves and that particular potato will stop growing.

Hens have to be given foods which contain calcium so that they can make the shells for their eggs. Radio-isotope experiments have shown that the calcium does not go directly to the manufacture of eggshells. The calcium is first used to make the bones of the hen, and it is from the bones that the shells are made. In this way the skeleton of a laying hen is almost completely replaced once every two months.

Pest control

Pest control is an important matter for the farmer and here too radio-isotopes have scored distinct successes. In the islands of the Caribbean the screw worm fly lives and feeds on the open wounds of animals, making them unfit for use as food and sometimes even killing them. There are so many of these flies that it is impossible to kill them all. After some time American scientists hit on an ingenious solution to this problem. They irradiated male screw worm flies so that they became sterile—when they mated no new screw worm flies would hatch out. The female screw worm fly only mates once and so by dropping large numbers of the sterile male flies from aircraft these pests were soon eliminated.

Pests such as weevils and grain beetles attack and destroy large quantities of stored grain each year. Estimates of such losses vary from 5 per cent to 50 per cent in various parts of the world. Here gamma irradiation holds out possibilities of getting rid of these pests while leaving the grain itself unaffected.

Preservation of food

Research is also showing how food can be preserved by gamma irradiation. At the moment there are signs that the storage life of meat can be increased by some four or five times the normal period. This work is still in the experimental stage and sometimes the irradiation changes the flavour of the food, or produces other unwanted effects. Even when these problems have been solved extensive trials have to be made to check that food preserved in this way is harmless to those who eat it. Feeding trials by human volunteers are already under way.

Medicine

Radio-isotopes are already being used extensively in many hospitals and medical research centres all over the world. These studies are gradually showing us exactly how the body works and are enabling diseases to be diagnosed and cured more easily.

By injecting a salt solution labelled with radioactive sodium 24 the path of these sodium atoms can be traced in the blood stream. In one method the active salt solution is injected into the foot and the time it takes to reach a counter placed over the groin is measured using a stop watch. For people with normal blood circulation this takes, on average, 18 seconds: for some it takes as little as 4 seconds and others as long as 51 seconds. Times longer than this indicate a fault in the blood flow, perhaps a small blood-clot (thrombosis) forming. Tablets can then be given to the patient which will dissolve the obstruction. Left undetected the blood clot may well grow and cause a stoppage of the blood which could result in the death of the patient.

In a similar way the exact position of a tumour (an unwanted growth) in the spine can be found. A small bubble of radioactive gas is introduced into the spinal fluid. This bubble will rise until it meets some obstruction—the tumour. By moving a small counter along the spine as the bubble of radioactive gas rises the exact place where it stops, and therefore the exact location of the tumour, can be found. The surgeon then knows exactly where to operate to remove the tumour. It is not possible to detect such tumours using X-rays, so here again radio-isotopes have proved an advantage.

Gamma rays from cobalt 60 or caesium 137 are used in the treatment of various forms of cancer. The gamma rays destroy the unhealthy cells in preference to healthy ones. However, if they are left on long enough the gamma rays will destroy the healthy tissue as well. To avoid this the beam of gamma rays is carefully focused on the spot where the cancer is situated. During the treatment the source slowly moves round the body of the patient. In this way the gamma rays always hit the cancerous growth but go through different parts of healthy tissue on the way there. This makes sure that the rays are never on the healthy tissue long enough for it to be destroyed. The unhealthy tissue, however, gets the full dose and so is destroyed.

Such machines must be made so that the intense gamma radiation is only allowed out in a narrow beam. This is done by putting the cobalt 60 or caesium 137 inside a large block of lead. The size of the opening and the direction of the beam is set by the operator. Because the beam is so intense, the operator would be exposed to small amounts of radiation each and every day and this would eventually prove dangerous. When it is on, the machine is therefore operated remotely from a separate control room. The operator can watch the patient either through a window, or in close-up by closed-circuit television.

The way in which the human body absorbs and uses various elements is also important. These include cobalt, iron, calcium, iodine, and many others. Studies using radioactive iodine 131 have shown how this element is absorbed in the body and becomes concentrated in the thyroid gland in the neck. Sometimes the cells of the thyroid multiply too quickly and the neck of the patient becomes very swollen—a goitre is formed. Until radioactive iodine was used the only way of curing this was for the surgeon to remove the extra cells. Now, if surgery is inadvisable a fairly strong dose of radioactive iodine can be given—it is simply dissolved in water and the patient drinks it. The iodine 131 concentrates in the thyroid cells and so the radiation is strongest there and some are destroyed. A careful calculation tells the doctor the correct dose to give so that the unwanted thyroid cells are destroyed but leaves undamaged the correct number to continue the normal working of the gland.

Sterilization

Disease-carrying bacteria can also be killed by irradiation. This is particularly important in hospitals where bedding has to be sterilized (freed from bacteria and other disease-carrying organisms) before it can be safely used again. Woollen blankets can only be steam sterilized two or three times before they are ruined by the heat. But by using radiation the blankets can be sterilized as many as twenty times before they become unfit for use. This is because the radiation does not raise the temperature very much and so the woollen fibres are not damaged to the same extent as they are by the steam. Since the temperature does not rise appreciably this is known as cold sterilization.

Cold sterilization is used in other departments as well. When surgical instruments are manufactured they are packed in plastic envelopes and then sterilized by radiation. This type of sterile packaging is particularly useful for emergency equipment which may have to be used quickly, or where there is no ordinary steam sterilizing equipment available.

Drugs such as penicillin and streptomycin, whose effectiveness is destroyed by heat, have up till now been sterilized by a complicated filtering process. Irradiation after packing now sterilizes these drugs more easily and completely than before.

Industry

We have already seen some of the results of industrial research using radioisotopes in Chapter 14. Further research projects are exploring the possibilities of producing plastics which will withstand heat. This is done by gamma irradiation. In industry a process must not only give the required product, but must give it cheaply enough for the product to hold its own in competition with other similar products. Still further research will be necessary before such plastics can be made available on a large scale.

Another interesting piece of industrial research has been done on the vulcanizing of rubber for tyres. When rubber is vulcanized in the ordinary way it is treated with sulphur and heated to increase its strength and elasticity. Irradiation was also found to produce the same effects without the use of sulphur. The interesting thing here, is that this led to improved chemical vulcanizing which at present is better than vulcanization by irradiation.

So radioactive isotopes do not give the complete answer to every problem. They have, however, been extraordinarily successful in many problems which could not be solved by more usual methods.

Chapter 16

Making a miniature sun

All the particles and rays we have been talking about have obtained their energy from the fission of heavy nuclei. The sun gets its energy in exactly the opposite way: from the bringing together of light nuclei to make heavier ones. In the sun, nuclei of hydrogen are brought together to form helium. Neutrons are also produced, as shown in Fig. 62. Two things which join together in this way are said to fuse. This kind of reaction is therefore called a fusion reaction.

The sum of the masses of the helium nucleus and neutron formed in this fusion reaction is less than the total mass of the hydrogen nuclei. The difference in mass being 0·00359 units. Using Einstein's equation $E = mc^2$ this mass difference represents an energy release of 3·34 MeV for each pair of hydrogen nuclei which fuse. In a fusion reaction many millions of pairs of hydrogen nuclei fuse and so the energy released is consequently very large. The sun, remember, can burn you when you are lying on a beach over 92 000 000 miles away.

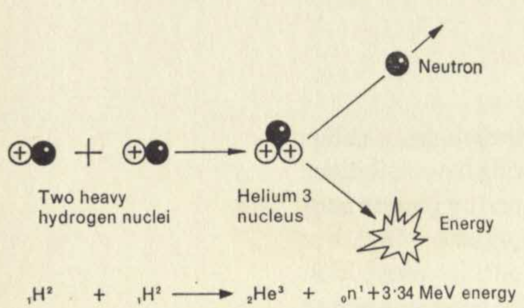

Neutron
Two heavy hydrogen nuclei
Helium 3 nucleus
Energy
$_1H^2 + {}_1H^2 \longrightarrow {}_2He^3 + {}_0n^1$ +3·34 MeV energy

Fig. 62
One possible fusion reaction.

The gas heavy hydrogen (hydrogen which has a neutron as well as a proton in the nucleus) is used to try and make such a fusion reaction in the laboratory. Heavy hydrogen can be extracted from water. A reactor which used fusion as its source of power would thus have an inexhaustible supply of fuel. One gram of heavy hydrogen—the equivalent of about 8 tons of coal in terms of power produced—can be extracted from water for a few shillings. A fusion reactor will also have the advantage of not producing dangerous radioactive by-products; although workers operating the reactor will have to be protected from the neutrons which are given off. It might even be possible to produce electricity directly, without the use of conventional generating machinery.

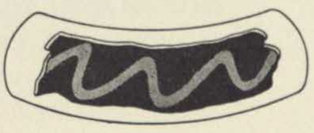
In order to see if fusion reactions using heavy hydrogen are a practical proposition a team of scientists at Harwell built an apparatus called ZETA. The letters stand for Zero Energy Thermo-nuclear Assembly. Zero energy since it does not produce surplus energy for generating power, and Thermo-nuclear Assembly because it is an assembly for producing nuclear reactions by heating.

In fact, to get the nuclei of the heavy hydrogen to fuse, temperatures of over 1 000 000° C have to be used. This is in order that the nuclei will be travelling fast enough to overcome the large forces of repulsion between the positive charges they carry. In ZETA this is done by passing a very large current of electricity through the gas. The heavy hydrogen is enclosed in an aluminium tube shaped like the inner tube of a motor car tyre.

The current is fed to the gas by means of a transformer. A transformer converts a small current under a high potential difference in the primary circuit, into a large current under a small potential difference in the secondary circuit. This only happens when the current is changing: when the current is first switched on for example, it changes from zero to its maximum value in a very short time. The power, (volts times amps), is almost the same in the secondary as in the primary. Almost, because some power is used up in driving the current through the circuit. The transformer in ZETA works like the transformer in a radio set, but is much bigger. The primary coils are wound on steel rings which are 10 feet high and weigh 150 tons. The secondary winding is the ring of gas inside the aluminium tube. In this way the gas gets the maximum amount of current through it—up to 270 000 amperes.

Naturally, when this current heats the heavy hydrogen to over 1 000 000° C anything in contact with it would simply vaporize. The hot gas must therefore be kept away from the walls of the tube. Whenever an electric current passes through a wire it also produces a magnetic field round the wire. In ZETA this magnetic field is due to the current passing through the gas itself. The effect of the magnetic field is to 'pinch' the gas in the centre of the tube and thus keep it away from the sides. But it was soon found that this was not the complete answer to the problem. Sometimes the hot gas wriggled violently, touched the side of the tube and used its energy up in vaporizing the tube wall. This meant that really high temperatures could not be attained. This difficulty was solved by winding further current-carrying coils round the whole length of the tube. The current in these coils produced a magnetic field along the centre of the tube and this had the effect of reducing the size of the wriggles so that the hot gas no longer touched the walls.

Hot gas wriggles violently when 'pinched' by magnetic field



The magnetic field due to additional current-carrying coils keeps hot gas in centre of tube

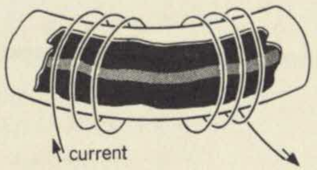


Fig. 63

Preventing the hot gas from vaporizing the tube containing it.

In early experiments with ZETA temperatures of from 1 000 000° C to 5 000 000° C were obtained for periods of up to three-thousandths of a second.

Before we can hope to get any useful energy out of such fusion reactions, temperatures of from 80 to 350 million degrees Celsius will have to be held for periods of about one second. When we can do this we will just about break even, that is, the energy produced by fusion will just balance the energy put in plus that lost to the surroundings.

Further improvements will then have to be made so that the energy produced by fusion will exceed this amount. And finally, there will be the development of electrical power stations to convert this heat energy into electricity.

There is still obviously a very long way to go before a fusion power reactor will be a practical proposition. It will require all the skill of many technicians and scientists to bring it about.

Chapter 17

The Future

In this book we have seen some of the ways in which scientists have discovered what atoms are like and how they behave. As a result of this knowledge they have been able to release the tremendous energy locked in the nucleus. This energy can be released quickly, producing the destructive explosion of a nuclear bomb; or it can be controlled to produce power for the generation of electricity, to drive ships and make radio-active isotopes which have so many beneficial uses for mankind.

In their search for knowledge physicists are continually finding out more about the structure of the atom. For example, they have now discovered that the neutron and proton themselves have a structure. They both have a core of dense positive charge surrounded by two clouds of more diffuse charge. In the case of the neutron the inner cloud bears a negative charge, while the core and outer cloud are positive. Outside the neutron the effects of these positive and negative charges cancel each other so that the neutron behaves as if it were neutral throughout. For the proton the core and both clouds have positive charges. These new developments indicate that the picture of an atom with a nucleus consisting of protons and neutrons which is surrounded by orbital electrons is altogether too simple. Further research will undoubtedly bring many more facts to light and these may well affect the development of nuclear power both for military and peaceful uses.

In the military sphere new developments are obviously on the secret list. Military experts are learning how to control the nuclear explosion and make smaller, more compact weapons which will accomplish their purpose without spreading harmful radiation which would affect friend and foe alike. While world tension continues vast amounts of money will be spent on such projects —and it is tantalizing to think how much real progress would be made if similar resources were available for the development of the peaceful uses of nuclear energy.

There is no means of halting this colossal mis-use of money until all the nations concerned agree to ban the production and testing of nuclear armaments. Before such an agreement could come into force some form of international control must be worked out. This is not easy. The detection of explosions by a world-wide chain of monitoring stations equipped with seismographs (instruments for detecting the earth tremors produced by the explosion) is not satisfactory because methods of cancelling out the earth tremors have been developed. So even if such monitoring stations were set up any nation which so wished could conduct underground tests in secret without risk of detection. At the moment there would seem to be only two effective methods of control. First, some form of international police force with powers to inspect the nuclear programmes of all countries wherever and whenever it wished. Second, that all military nuclear research programmes be taken over by an international body; this body would have to control everything—weapon tests, stockpiles, manufacturing processes, and research facilities.

That international co-operation can be obtained in furthering the peaceful uses of nuclear energy has been shown by the creation of Euratom (The European Atomic Energy Community), the European Nuclear Energy Agency, and the International Atomic Energy Agency. For example, Euratom (Member States: France, Western Germany, Italy, Belgium, The Netherlands, Luxemburg) has established a common market for nuclear materials and for the equipment necessary to build nuclear plant. It is also perfecting a comprehensive system of sharing technical information while still protecting normal patent rights. Good though such co-operation is, it is not enough. What is needed is an all out attack on outstanding problems. A truly international research centre should be set up for each problem. Take the problem of the fusion reactor suggested by ZETA. Such an international research centre set up to deal with this single problem and staffed by teams of scientists from every country would have the resources and man-power to make fusion power practicable far, far sooner than present piecemeal research on a national basis. Similar centres could attack other problems such as cancer or the production of more food to keep pace with the world's rapidly increasing population.

The logic of such a scheme is inescapable. To realize it in practice means that men will have to change their way of thinking; they will have to become internationally minded rather than nationally minded. This is a very slow process. However, no-one whether young or old, should be without some knowledge of nuclear energy and its applications. Used properly it can be of enormous benefit to mankind; the terrifying alternative is destruction. We must see that its destructive powers are never used and that the peaceful uses of nuclear energy are fully exploited to the benefit of all mankind.

Glossary of Terms

Atom	An atom is the smallest part of an element which can take part in a chemical reaction.
Molecule	A molecule is the smallest part of an element or compound which can exist alone. It may consist of one or more atoms joined together.
Ion	An ion is an electrically charged atom or group of atoms.
Electron	Electrons are found in all atoms, they have a charge of $-e$ and a mass of $\frac{1}{1840}$ times that of a hydrogen atom.
Alpha particle	An alpha particle has a charge of $+2e$ and a mass of 4 units. A mass unit is one twelfth of the mass of a carbon 12 atom.
Beta particle	A beta particle is an electron.
Gamma ray	A gamma ray is an extremely short wave radiation with a wavelength of about 1 ten thousand millionth of a centimetre.
Proton	A proton is a particle which has a charge of $+e$ and a mass of 1 unit.
Nucleus	The nucleus is the positively charged central core of an atom. Almost all the mass of the atom is concentrated in the nucleus.
Neutron	A neutron is a particle which has no charge but which has a mass of 1 unit.
Atomic number	The atomic number of an element is the number of protons in the nucleus of each atom of the element.
Isotope	Isotopes are different forms of the same element in which the atoms, although they have different masses, behave in the same way chemically.
Half-life	The half-life of a radioactive element is the time it takes for half the atoms present at any given time to decay, i.e. shoot out alpha or beta particles or gamma rays and so become atoms of a different element.

When it all happened

1808	John Dalton's atomic theory was published.
1876	Cathode rays discovered and named by E. Goldstein.
1895	Röntgen discovered X-rays.
1896	Becquerel discovered radioactivity.
1897	J. J. Thomson showed cathode rays were streams of electrons.
1898	J. J. Thomson's picture of the atom.
1899	Rutherford detected alpha and beta rays.
1900	Gamma rays discovered by P. Villard.
1905	Einstein discovered the equivalence of mass and energy: $E = mc^2$.
1909	Rutherford showed that alpha particles are parts of helium atoms.
	Geiger and Marsden investigated the scattering of alpha particles by thin metal foils.
1911	Rutherford's picture of the nuclear atom.
	First cloud chamber made by C. T. R. Wilson.
	F. Soddy suggested existence of isotopes of radioactive elements.
1912	J. J. Thomson showed that stable elements also have isotopes.
1913	Neils Bohr's theory of the nuclear atom and circling electrons.
1914	Rutherford and Andrade showed that gamma rays are short wavelength X-rays.
1919	Rutherford used natural alpha particles to convert nitrogen into oxygen.
	Aston's 'atomic weighing machine'—the mass spectrograph.
1932	Cockcroft and Walton first men to accelerate protons and split lithium nuclei.
	Chadwick discovered the neutron.
1934	Fermi made elements radioactive by bombardment with slow neutrons.
1938/39	Hahn and Strassmann discovered nuclear fission.
1942	Fermi produced the first controlled chain reaction.
1945	Nuclear bomb devastated Hiroshima in Japan.
1956	Calder Hall—first large nuclear power station produced electricity.
1957	ZETA began working at Harwell for experiments on nuclear fusion.
1959	Dounreay fast reactor began operation.

Other books to read

The Walt Disney Studios have colourfully illustrated an account of atomic and nuclear research in *Our Friend The Atom* by Heinz Haber (Rathbone Books, 1956). Another book which describes modern views on the atom in story form is *Mr. Tompkins Explores The Atom*, by George Gamow (C.U.P., 1955); and Dr. J. Bronowski, well-known for his radio and television appearances on the Brains Trust, has answered ten fundamental questions about the atom in a booklet *The Atom* (Newman Neame Take Home Books, 1956). With the same title, *The Atom*, by Sir George Thomson (O.U.P., 5th edition 1956), gives a detailed account of work in this field—J. J. Thomson was Sir George's father. Sir George has also written a more general book, *The Inspiration of Science* (O.U.P., 1961), showing how physicists think, especially when engaged in research. He also gives fascinating personal glimpses of his father and other famous physicists.

Calder Hall—the story of Britain's first atomic power station, by. K. E. B. Jay (Methuen, 1956), shows how the principles of nuclear energy were applied in practice.

Two books which describe radioactive isotopes and their uses are *Labelled Atoms*, by Raymond Glascock (Sigma Books); and *Isotopes*, by J. L. Putman (Penguin Books, 1960).

An interesting book about the people who made all these discoveries is *Men and Women Behind the Atom*, by Sarah R. Reidman (Abelard-Schuman, 1957).

Information on careers with the United Kingdom Atomic Energy Authority may be obtained by writing to the Public Relations Branch, U.K.A.E.A., 11 Charles II Street, London S.W.1, or by calling at the Information Centre at the same address. The firms listed in the Acknowledgements at the beginning of this book also have departments connected with nuclear energy and its applications. For information about possible careers write to the Personnel Officer—you can find the addresses of these firms in the Trade Directories in your local Public Library.

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